PROF. RYSZARD STRZELECKI

IMPROVING POWER QUALITY IN DISTRIBUTION NETWORKS
POWER ELECTRONICS VS. HYBRID TRANSFORMERS

СПАСИБІ ІНСТИТУТУ

Закінчилося моє навчання у Київському політехнічному. Завершується один з найважливіших і найщасливіших періодів життя — студентський. І в ці хвилини хочеться звернути погляд назад.

Все почалося у рідній Польщі. Після першого року навчання в аграрно-технічній академії в Бидгощі успішно склав іспит з російської мови і приїхав до Радянського Союзу. Навчання у КПІ почав з другого курсу. Перші кроки — завжди нелегкі. Під час першої сесії отримав лише одну «четвірку», всі інші складав на «відмінно». Це була радість. А сьогодні 9 чоловік з 17 випускників із ПНР отримують дипломи з відзнакою.

Не хочеться розлучатися з однокурсниками. Шість років — краплина в історії століть, але час цілком достатній, щоб змогла народитися, вирости і зміцнитися справжня дружба між нами і радянськими студентами. Навчаючись на третьому курсі, почав працювати на кафедрі промислової електроніки під керівництвом доцента В. Я. Жуйкова. Тут пройшов добру школу наукової творчості. Набуті за цей період навики, безумовно, стануть у нагоді під час роботи на підприємстві.

Є у мене велика мрія: приїхати до Києва вчитися в аспірантурі.

Користуючись нагодою, хочу висловити велику вдячність всім викладачам, студентам і співробітникам інституту.

Рішард СТЖЕЛЕЦКІ,
випускник факультету електронної техніки.

Випускники 1981

Рішард СТЖЕЛЕЦКІ ПНР (факультет електронної техніки).

Юрій ЛЕНЧЕНК (теплоенергетичний факуль- тет).

Гонсалес Еміліо АРАУСО з Венесуели (електротехнічний факультет).

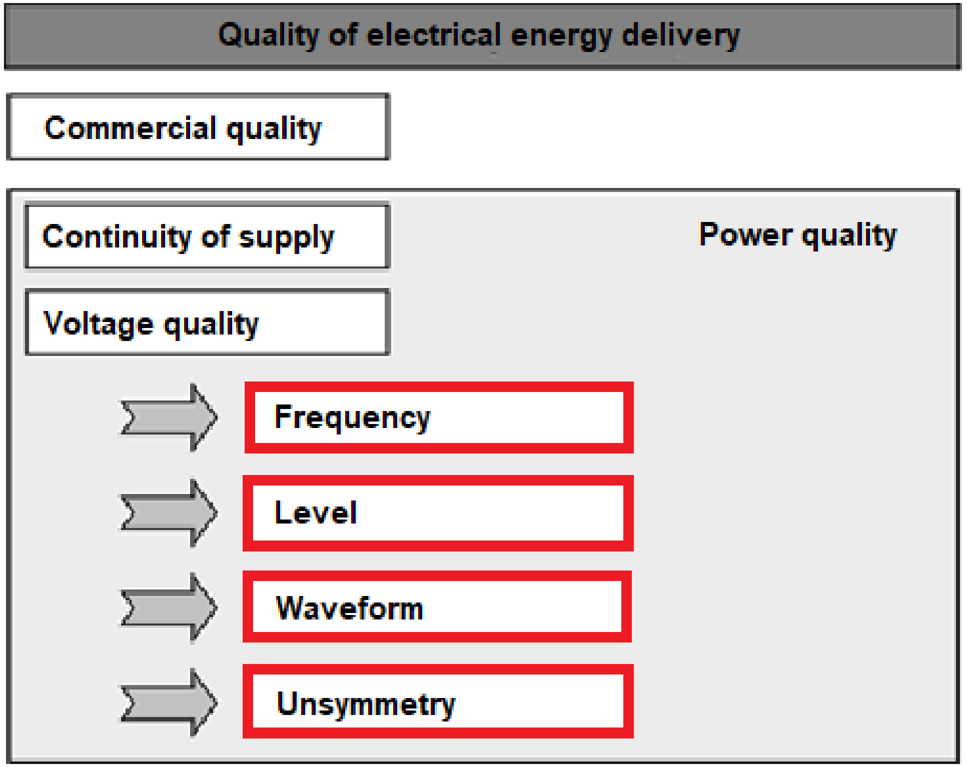
KIEV 21.12.2024

OUTLINE

1. Introduction
2. Different approaches to design of the Power Electronic Transformers (PET/DSST)
3. Hybrid Transformer
3. Conclusions

Introduction

Since the turn of the 20th/XXI century, including mainly in recent years, the operating conditions of the distribution network have changed significantly. Most modern loads draw constant power. In this case, the current of the load increases when the voltage decreases, compounding the voltage change problem. Also contributing to these changes is the large-scale introduction of distributed generation with a large share of renewable energy sources (RES), and the increasing number of applications of fast-change loads, such as fast chargers for electric vehicles. Under these conditions, the efficiency of using inertial (traditional) energy reserves is limited. **The outcome is problems in maintaining the required quality of electric energy (EE) supply.**

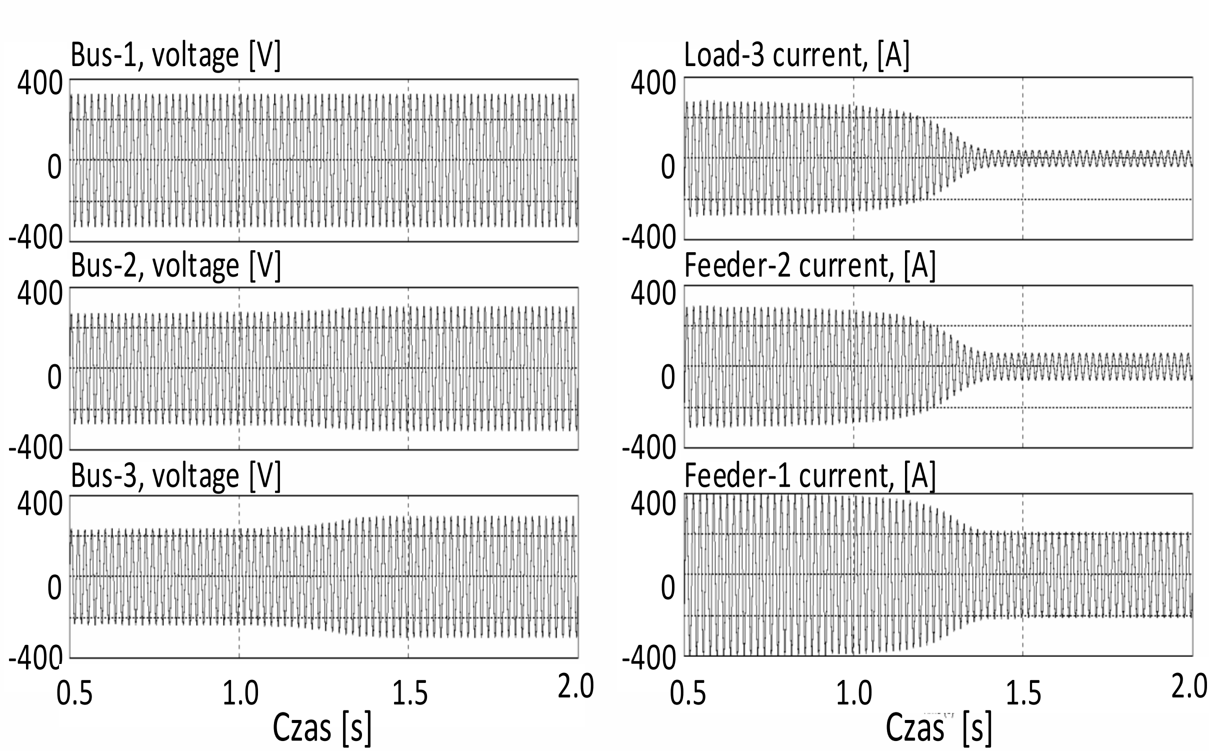


In the general sense also used by the Council of European Energy Regulators (CEER), quality of EE delivery includes the following areas:

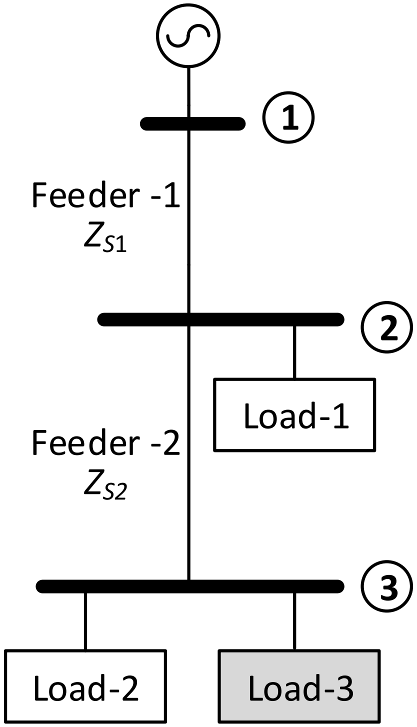
- Commercial quality, inter-preted as the quality of the relationship between the EE supplier and the customer,
- Continuity of supply related to power outages and other similar indices, including those determined on an individual basis,
- Voltage quality defined by numerical parameters evaluating a specific aspect of the difference between actual and reference (sinusoidal), waveforms under rated load current conditions.

Influence of Load on the Power Quality – Example 1

Voltage sags caused by a starting an squirrel cage induction motor



Single-line diagram of a simple power-distribution system

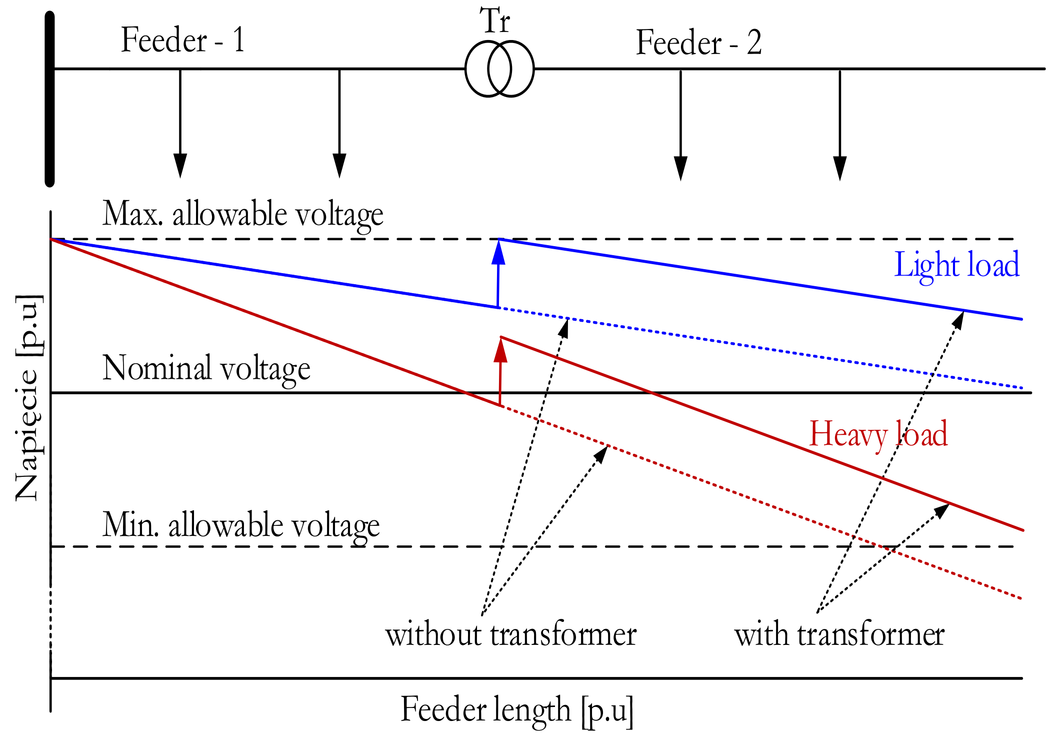


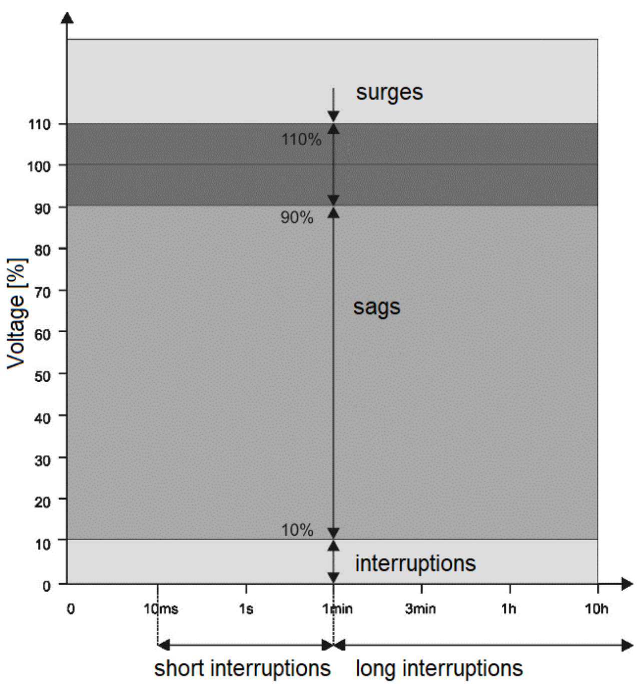
Load-1. Symmetrical *R-L* impedance: *S*=43 kVA , cosϕ=0.54
Load-2. Symmetrical ohmic resistance: *P*=15 kW
Load-3. Squirrel-cage induction motor: *S*=16 kVA, cosϕ=0.8.

Influence of Load on the Power Quality – Example 1

Light and Heavy Load Influence

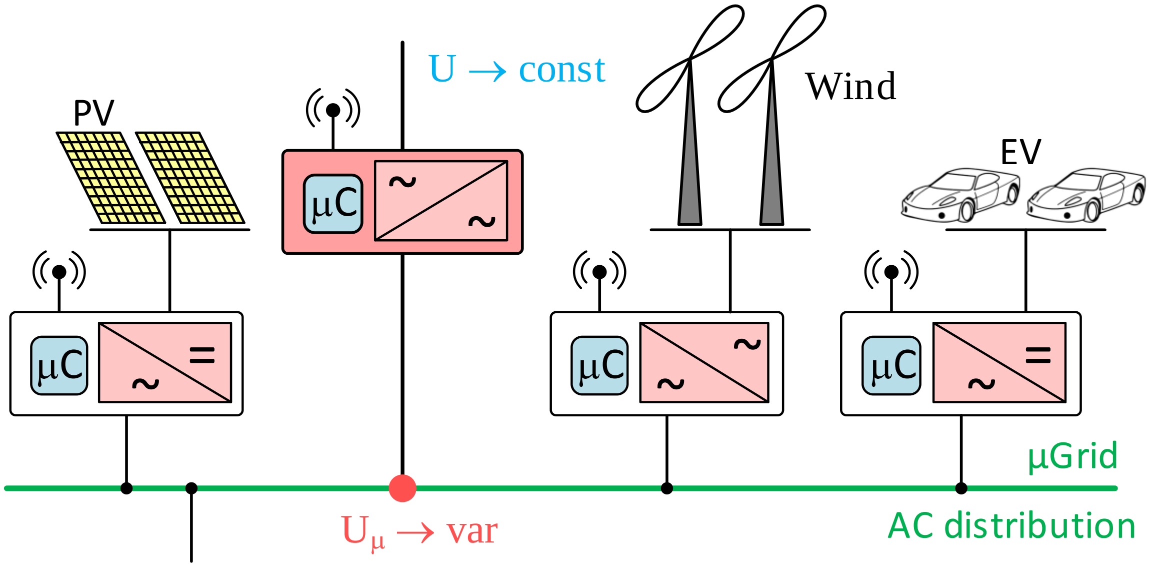
Typical voltage profile along a supply line with and without an additional transformer





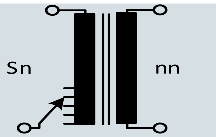
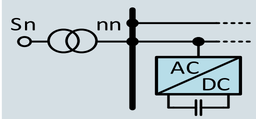
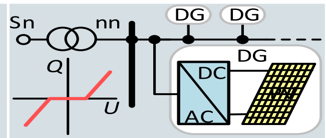
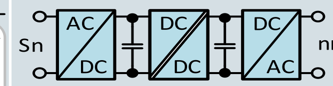
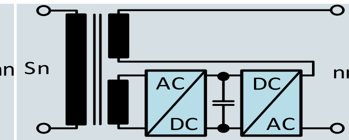
Classification of typical voltage disturbances affecting RMS

Examples of sources of grid voltage fluctuations

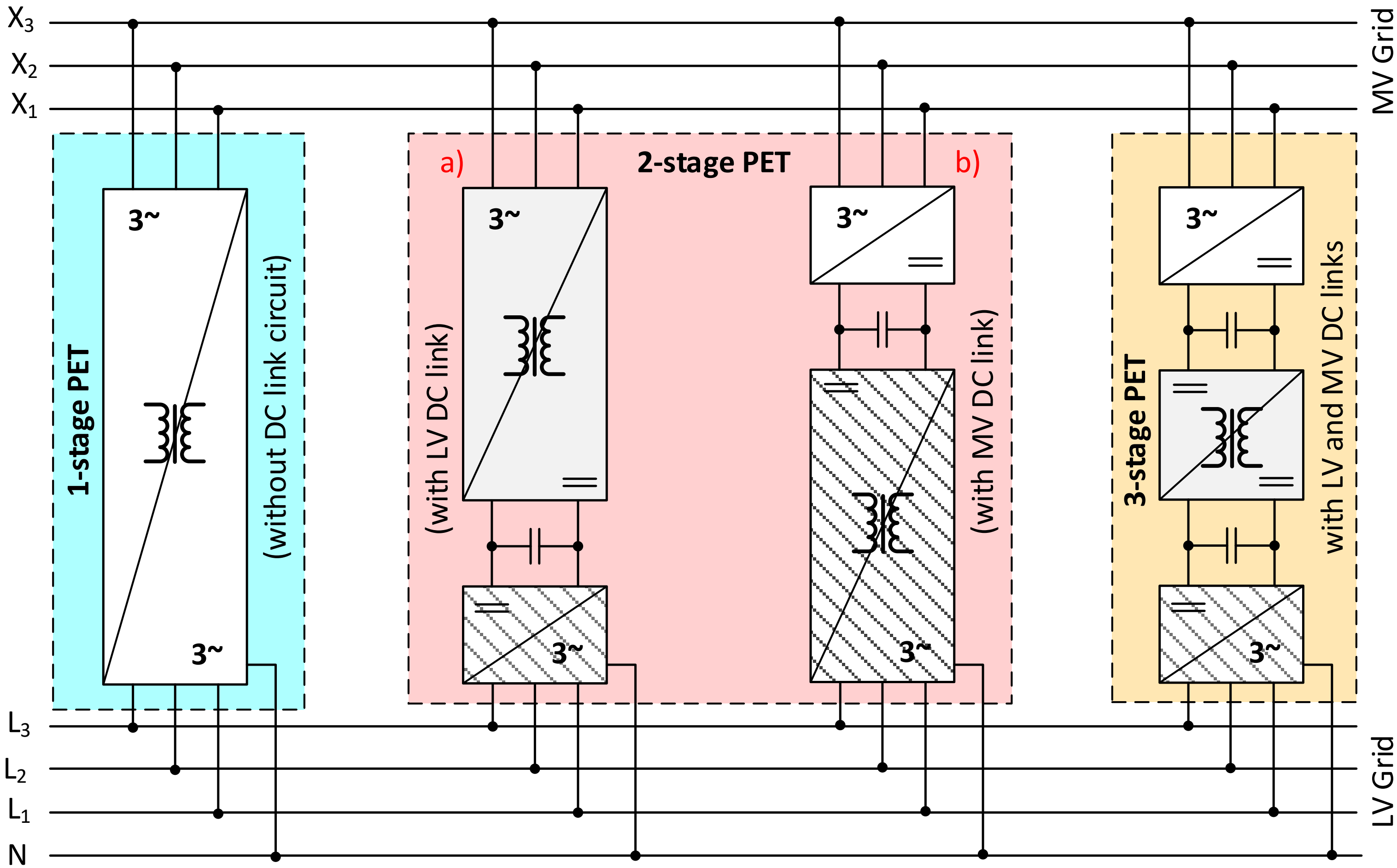


Mitigation methods used to improve voltage quality can be generally divided into 2 groups: a) organizational, b) technological (investment). The first group includes, for example: optimal distribution of loads in the grid; respect for standards, industry regulations and installation rules; even loading of 3 phases with 1-phase installations; coordination of the operating cycles of equipment connected to the grid, etc. **This group has the lowest costs, but the applied steps are often insufficient.**

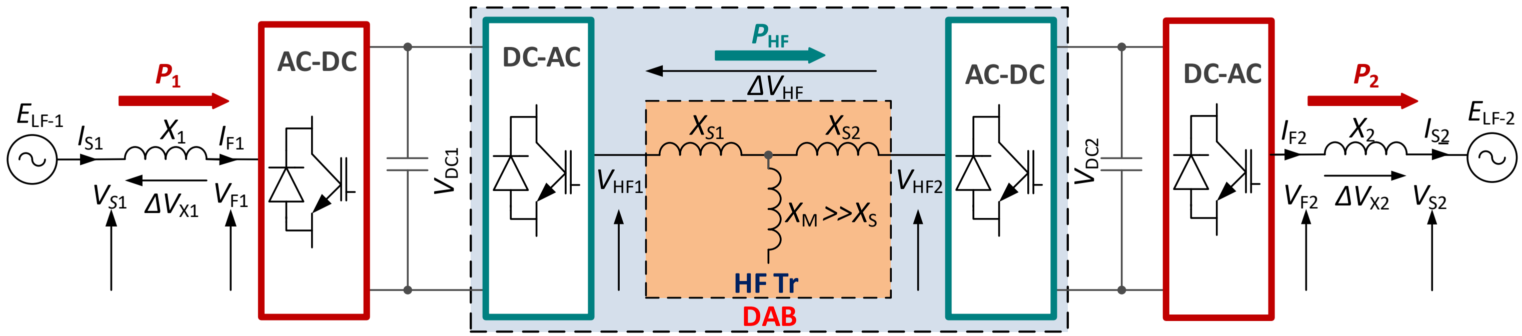
Key features of the main voltage improvement technologies

	VRTD	CPD (APC)	V-VCD	DSST	DTH
Scheme					
Adjustment range	U, P ~ ±10-20%	D-STATCOM, DVR: Q ~ ±40÷75% ; U ~ ±10÷50%; UPQC: U, P, Q ~ ±20%	Q ~ ±30÷40% ; U ~ ±0,3% ; for a single inverter	U, P, Q ~ ±100%	U, P, Q ~ ±10÷20%
Step, Dynamic	0,1– 5s per step of taps, (dependent on the type of OLTC)	Infinitely adjustable, very fast	Infinitely adjustable, very fast	Infinitely adjustable, very fast	Infinitely adjustable, very fast
Additional functions	------------	-Symmetrization; -Active compensation; -Power surge mitigation;	------------	-DC power supply -Symmetrization, -Active compensation -Power surge mitigation	- Power supply μGrid DC - Active compensation - Start-up mitigation
Relative efficiency	99% (power delivered)	D-STATCOM, ~98%, DVR: ~98%, UPQC: ~96% (converter power)	98% (converter power)	~94÷95% (power delivered)	~98,6% (power delivered)
Lifetime	40 years (service depending on OLTC type)	10 years	10 years	10 years	Transformer: 40 years, Converter: 10 years
Protection requirement	Yes	Yes	Yes	Practically as with conventional grids	IEC 60076 standard in combination with low redundancy
Status of technology	Commercial status	Commercial status	Commercial status	Laboratory prototype	Demonstration prototype
Typical applications	Grid with moderate voltage fluctuations	Modernization under the requirement of high dynamics	Local control (usually in connection with VRDT)	Supply of DC and hybrid DC-AC grids	Future local grids: residential, industrial, railroad, etc.

DIFFERENT APPROACHES TO DESIGN OF THE PET

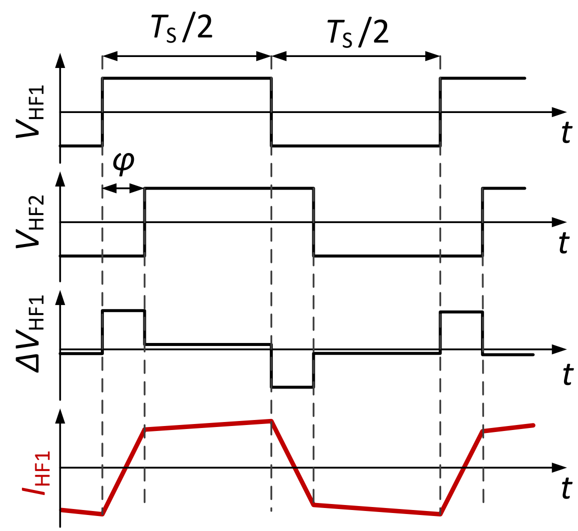


Principle of operation of 3-stage PET with DAB DC-DC converter



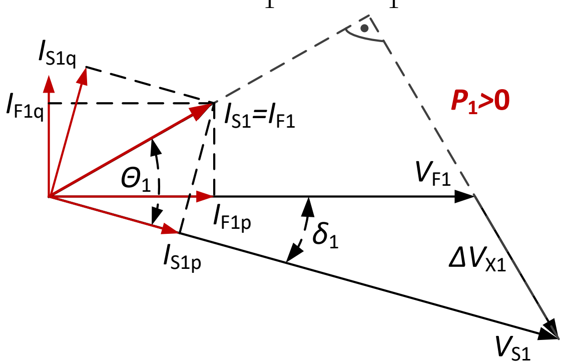
$$P_1 = \frac{V_{F1} V_{S1}}{X_1} \cdot \sin \delta_1$$

$$Q_{S1} = \frac{V_{S1}^2}{X_1} - \frac{V_{F1} V_{S1}}{X_1} \cos \delta_1$$

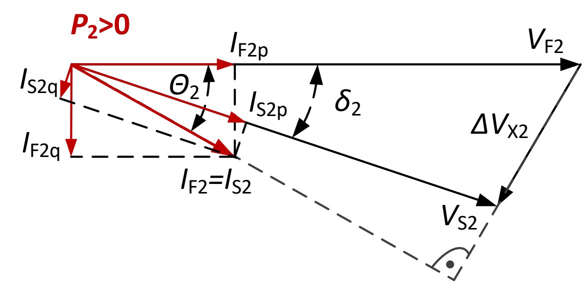


$$P_2 = \frac{V_{F2} V_{S2}}{X_2} \cdot \sin \delta_2$$

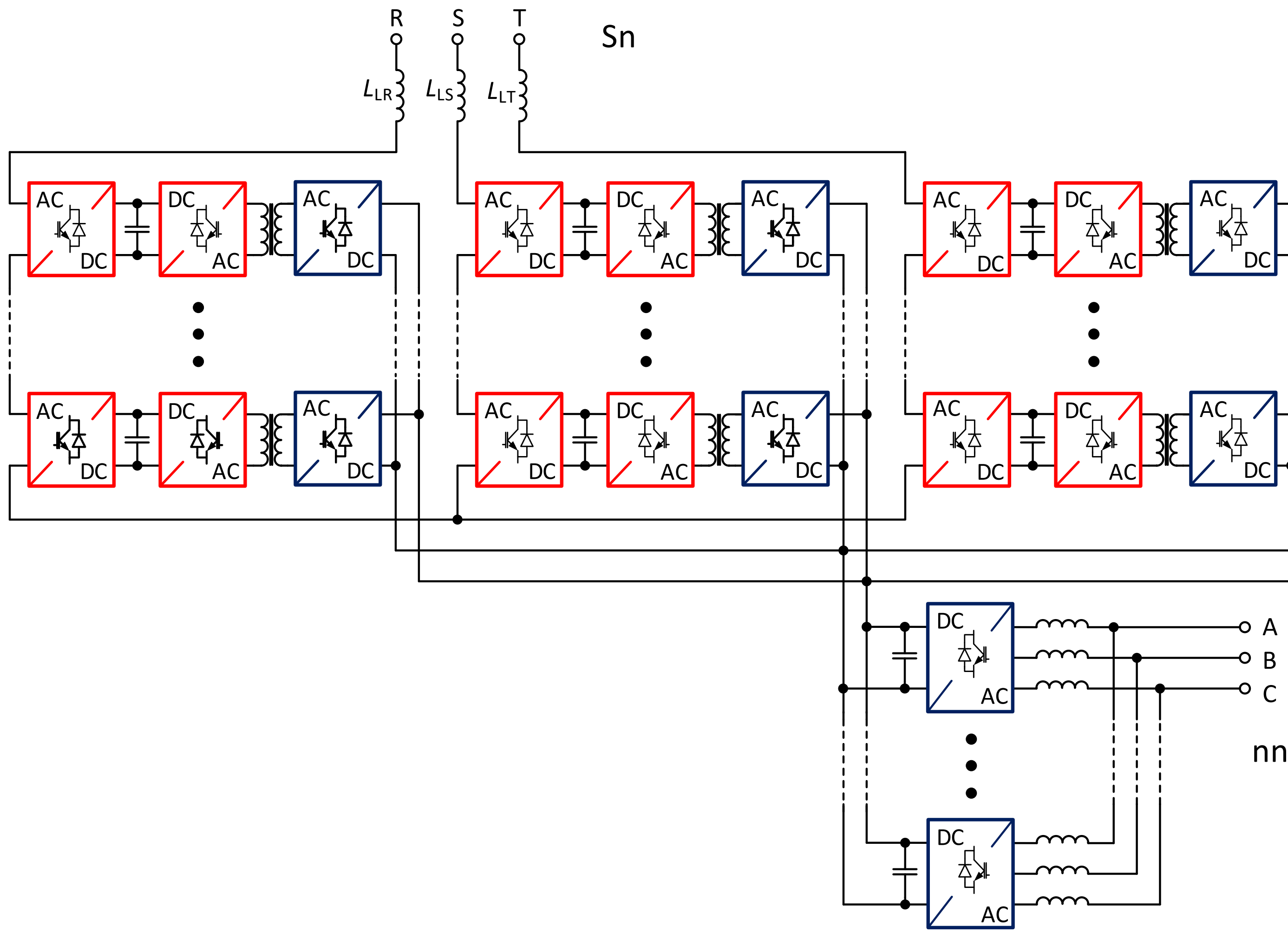
$$Q_{S2} = \frac{V_{F2} V_{S2}}{X_2} \cos \delta_2 - \frac{V_{S2}^2}{X_2}$$



$$P_{HF} = \frac{n V_1 V_2}{X_{S1} + X'_{S2}} \cdot \varphi \left(\pi - |\varphi| \right)$$

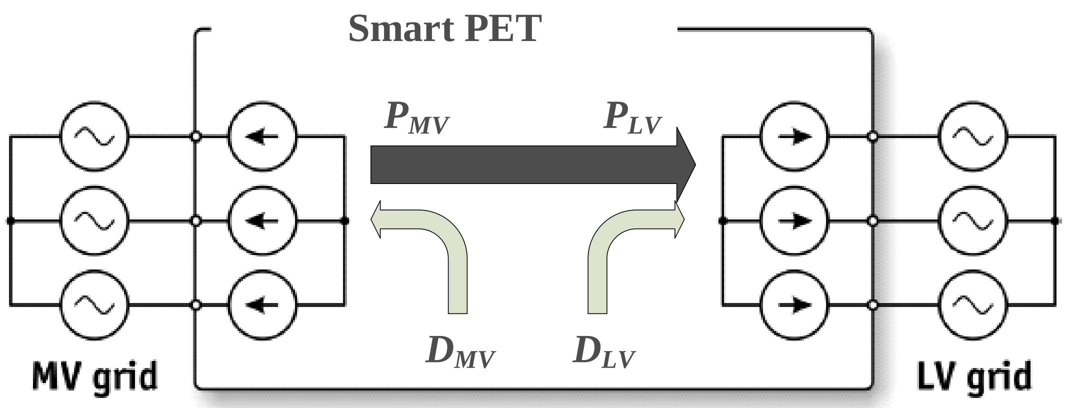


Typical modular 3-phase PET with 1-phase DAB converters

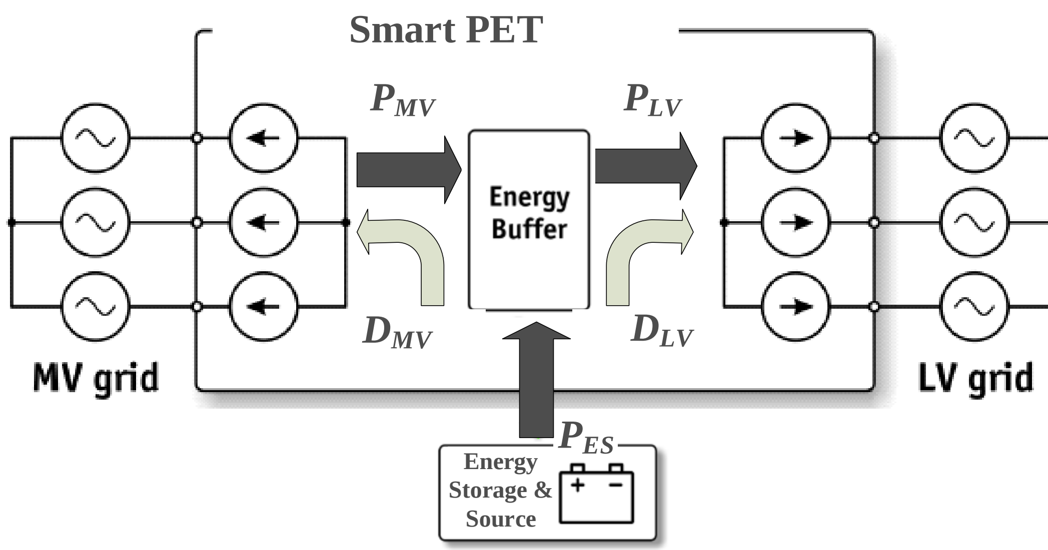


Smart PET funcionality

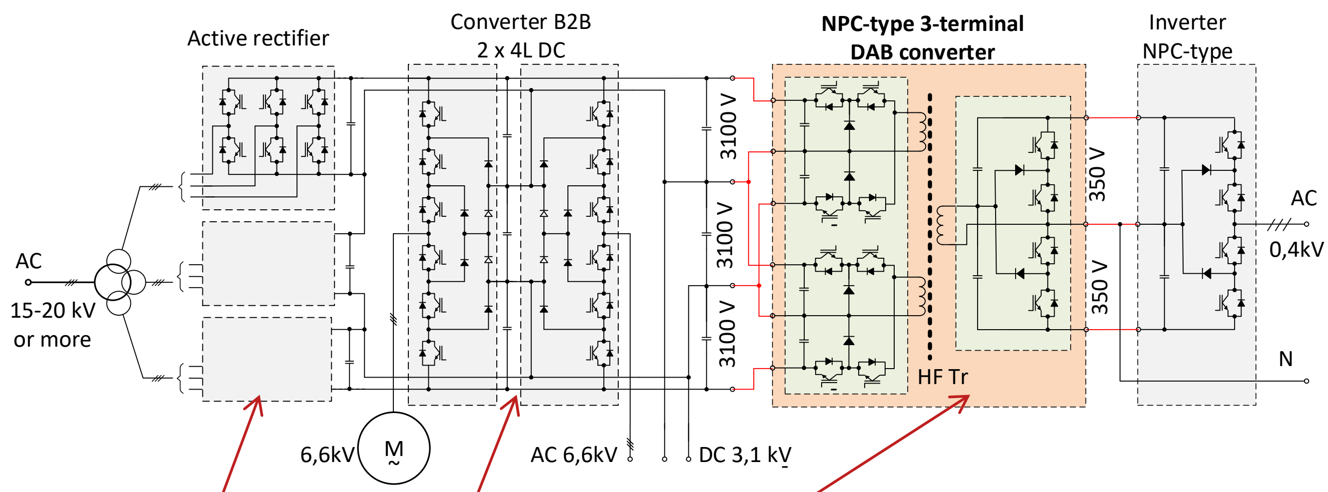
Power Control

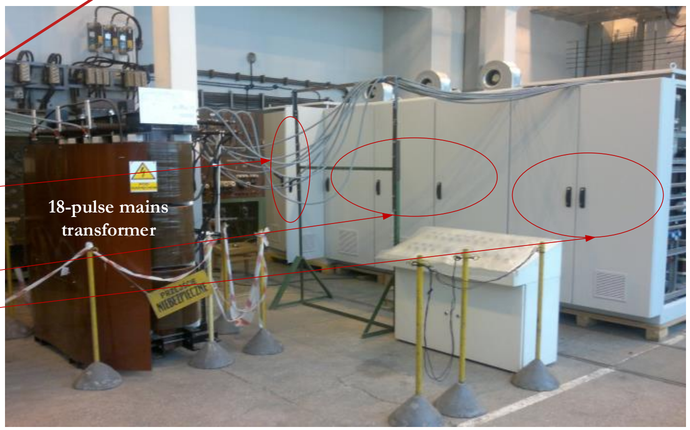


Power Control
&
UPS Operation
&
Interface Operation



Experimental model of a 5-terminal 1.5MW (4×AC, 1×DC) power distribution substation using a 3-stage 3-terminal PET with NPC-type DAB converter





Advantages and Disadvantages of PET (generally expected)

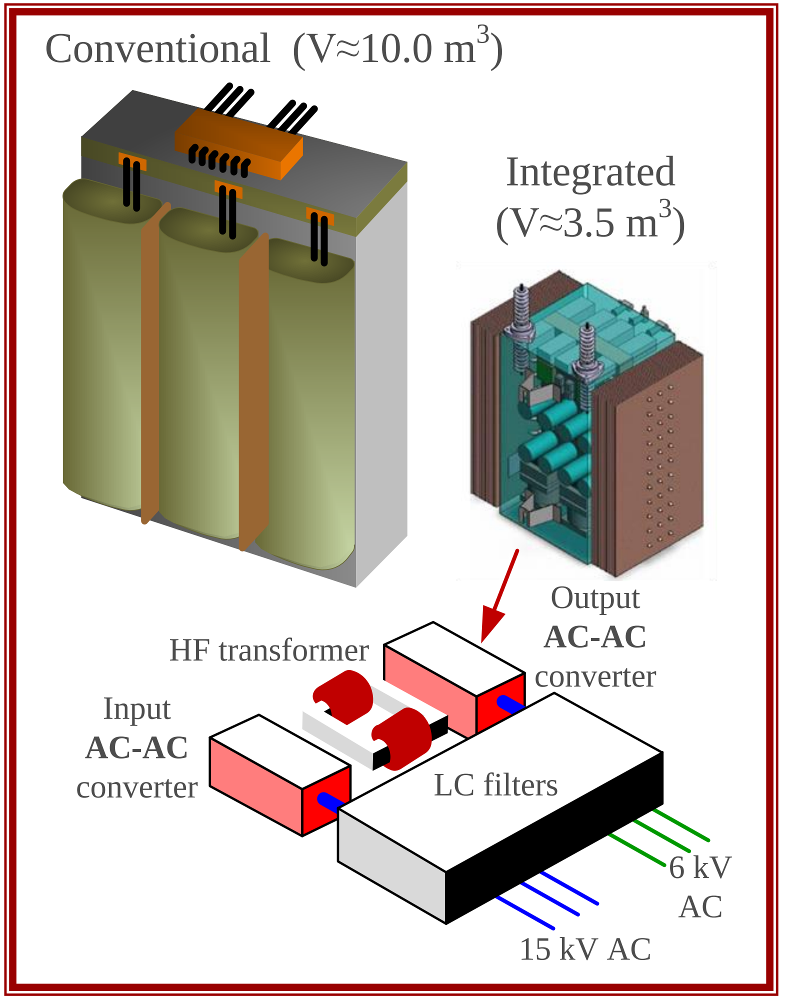
Advantages

- **Size/Weight Reduction** (Higher operating frequency reduces transformer size/weight) ???
- **Power Control** (Nonactive power compensation: var, unbalance & harmonic active compensation; active power flow control)
- **UPS Operation** (Linked to energy storage)
- **Interface Operation** (Linked to renewable source).

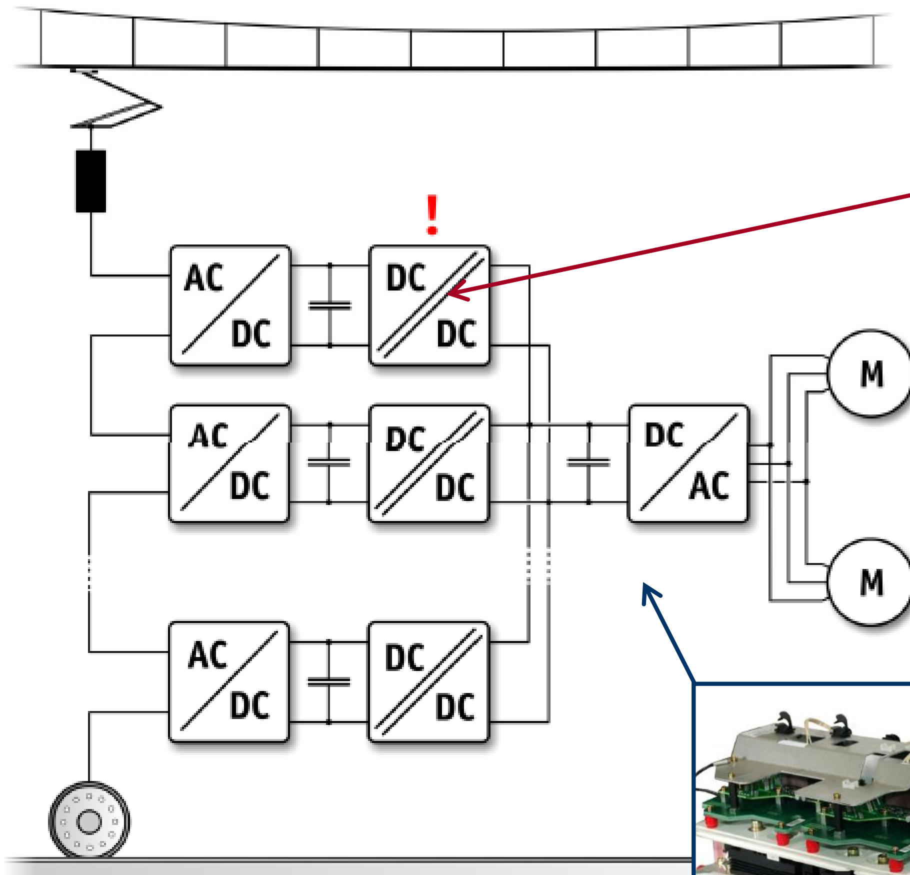
Disadvantage

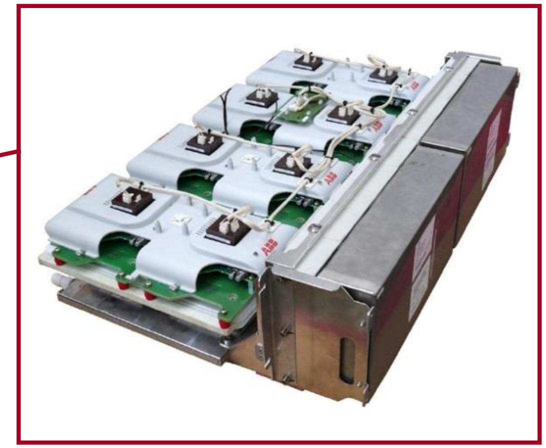
(compare to conventional transformer)

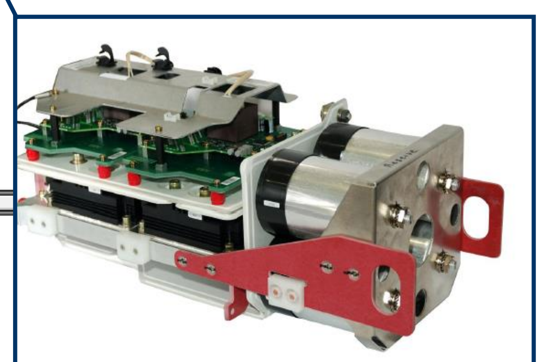
- **Less Reliability**
- **More complicated structure**



Potential applications of PET in traction research



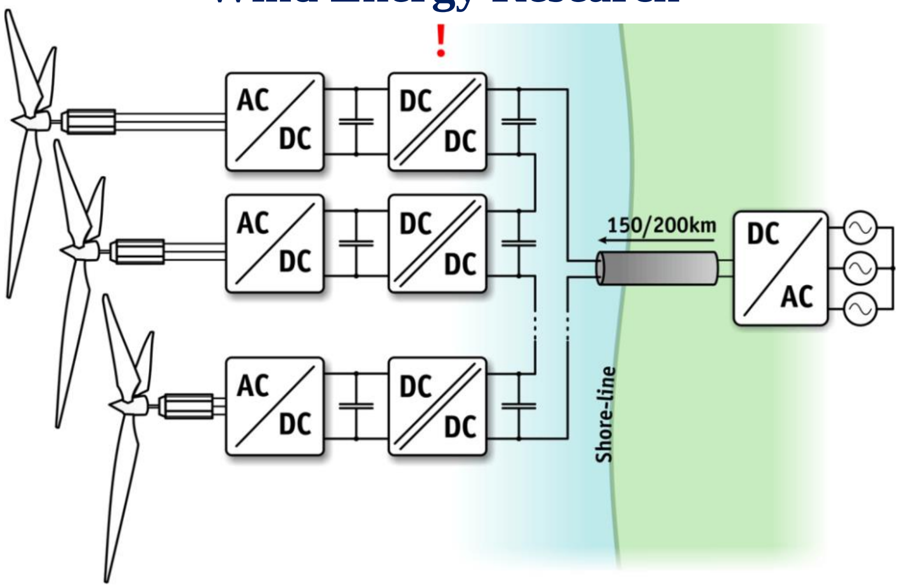




2001 - ABB (ETH)
2007 - Alstom
2007 - Bombardier
2009 - KTH
2010 - Erlangen

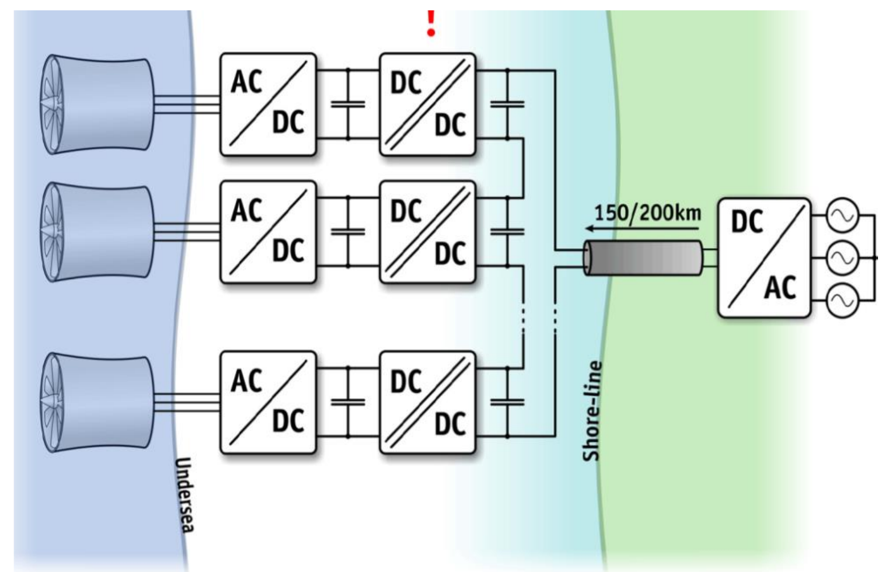
Potential applications of PET in renewable energy

Wind Energy Research

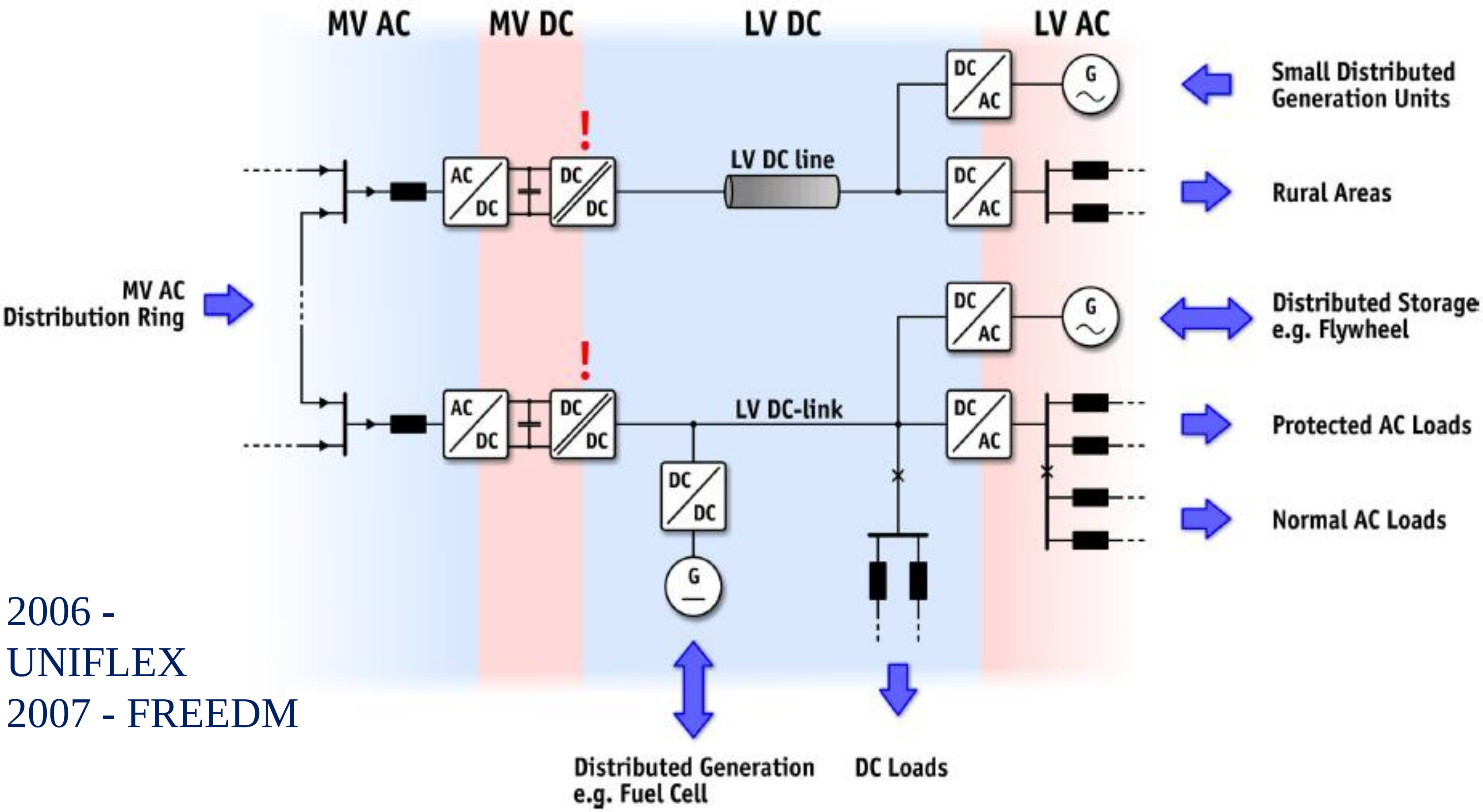


2009 - EON
2011 - L.2.E.P.

Tidal Power Research



Potential applications of PET in Smart Grids research

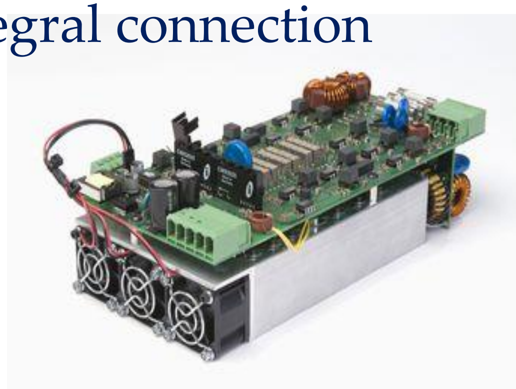


2006 - UNIFLEX
2007 - FREEDM

Hybrid Transformer

Main Concept

Integral connection



+

Img.: http://www.hieco-electric.com

Power Electronic Converter (PEC):

- Integral part of HDT;
- Sized for a fraction (10-15%) of DT power;
- Enables continuous voltage regulation in the +/-10%U_n range (PEC elements voltage ratings);
- Possible PEC circuit bypass, HDT operates like classic DT!

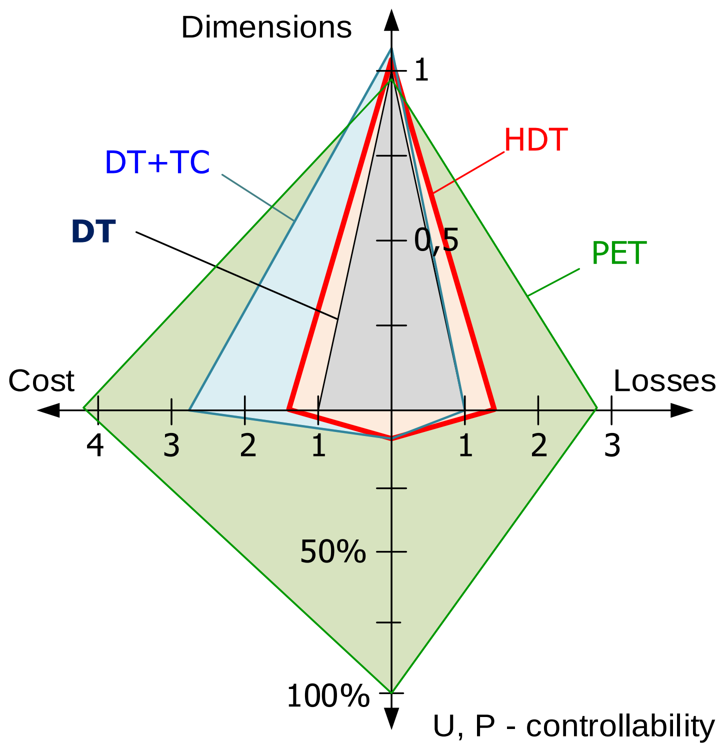
Classic Distribution Transformer (DT)

$$\eta_{HT} = \eta_{\mathbf{D}T} + \frac{\Delta}{100}(\eta_{\mathbf{PE}C} - 1) = 0{,}98 + \frac{10}{100}(0{,}95 - 1) = 0{,}975$$

General relative properties

Comparison of diferent distributed transformer:

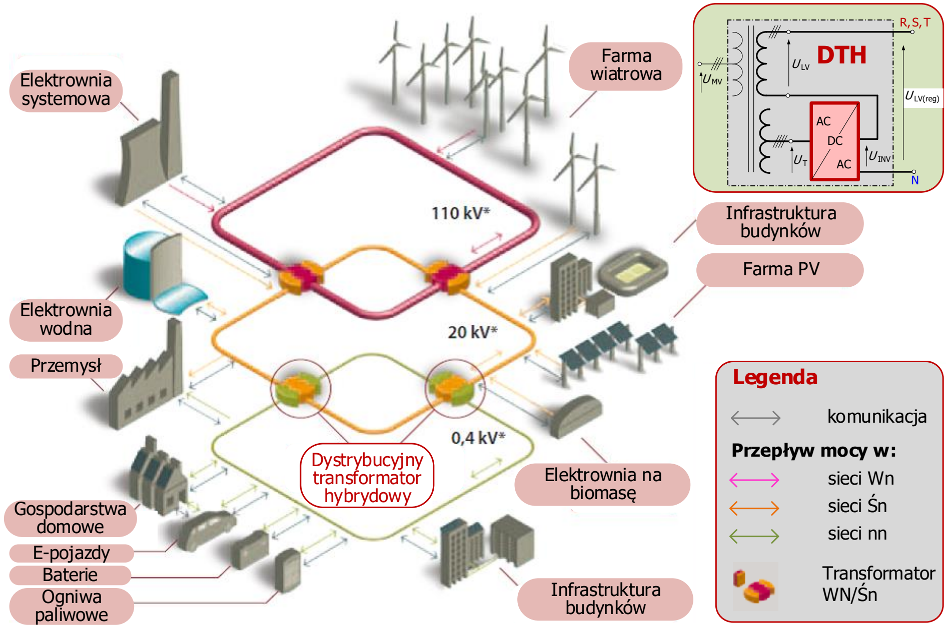
Hybrid (**HDT**) ; Classic (**DT**) ; Power Electronics (**PET**) ; Tap Changers (**DT+TC**)

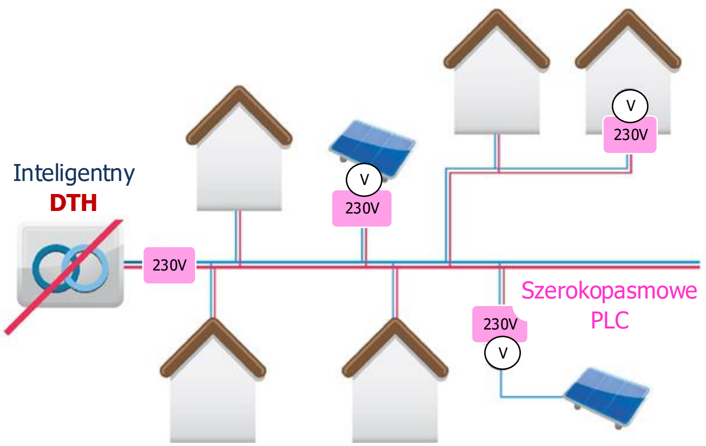


Functionality	HDT	DT	PET	DT+TC
Voltage regulation	continuous ±10%	-----	continuous ±100%	step ±10%
Dynamics of regulation	<20ms	-----	< 20ms	>100ms
Power factor regulation	ok. ±10º	No	±90º	----
Power flow control	ok. ±10%	No	100%	-----
Connection of DC source	10% P_N	No	100% P_N	----
Scalability and modularity	Yes	No	Yes	No

DTH in the energy system

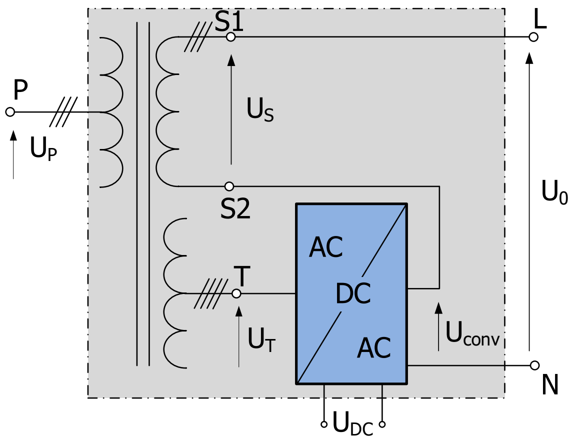
The location of DTH in the distribution system



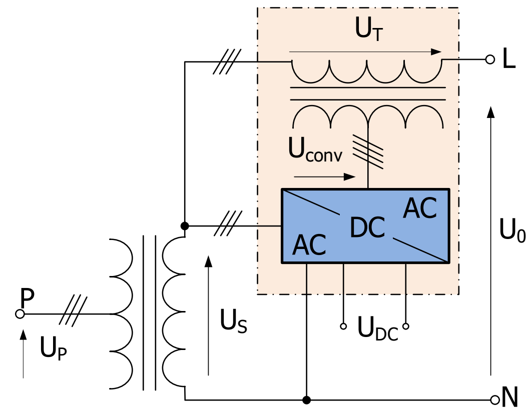


An example of a smart distribution substation with DTH, controlled by a broadband PLC in a LV grid

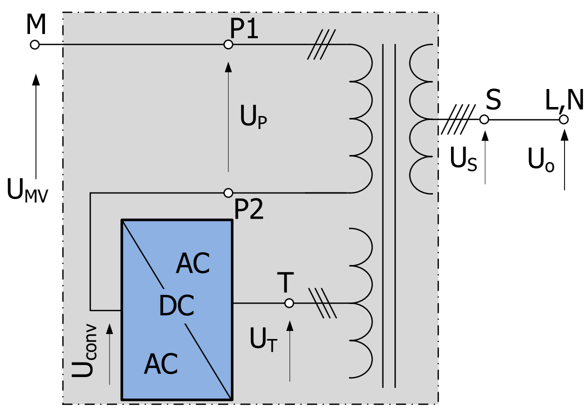
Basic developed DTH systems



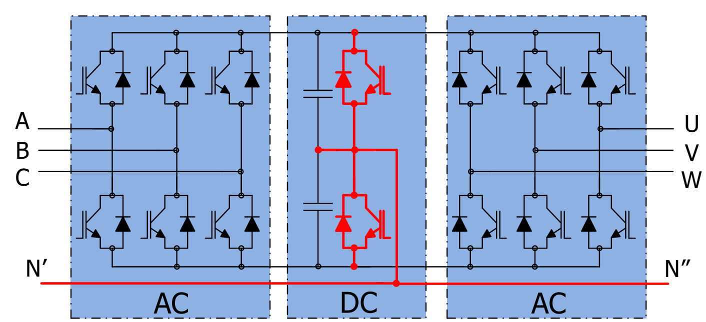
DTH integrated on the LV side



DTH with connectable stand-alone regulator on the LV side



DTH integrated on the MV side



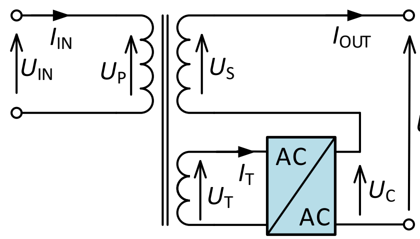
AC/DC/AC converter for use in in DTH systems on LV side

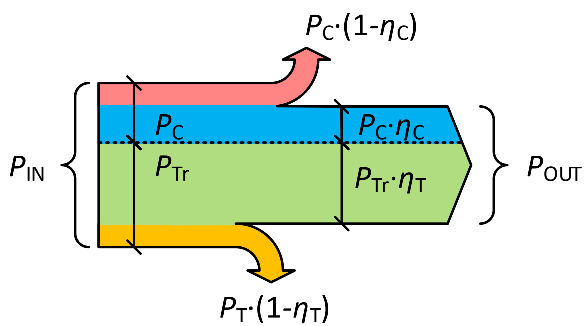
Power distributions in DTH systems with a converter on the

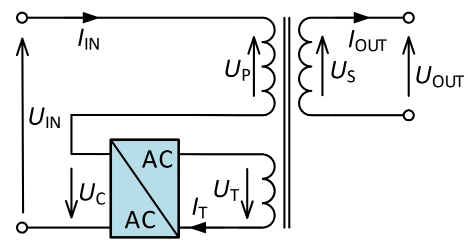
LV side and MV side

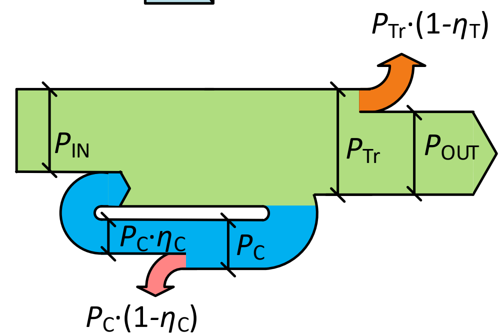
$$\eta_\Sigma = \frac{P_{OUT}}{P_{IN}} = (1-k)\cdot\eta_{Tr} + k\cdot\eta_C$$

$$\eta_\Sigma = \frac{P_{OUT}}{P_{IN}} = (1-k)\cdot\eta_{Tr} + k\cdot\eta_C\cdot\eta_{Tr}$$









$$P_{OUT} = P_{Tr}\cdot\eta_{Tr} + P_C\cdot\eta_C$$

$$P_{IN} = P_{Tr} + P_C \;;\; k = P_C/P_{IN}$$

$$\Downarrow$$

$$P_{OUT} = (P_{IN} - k\cdot P_{IN})\cdot\eta_{Tr} + k\cdot P_{IN}\cdot\eta_C$$

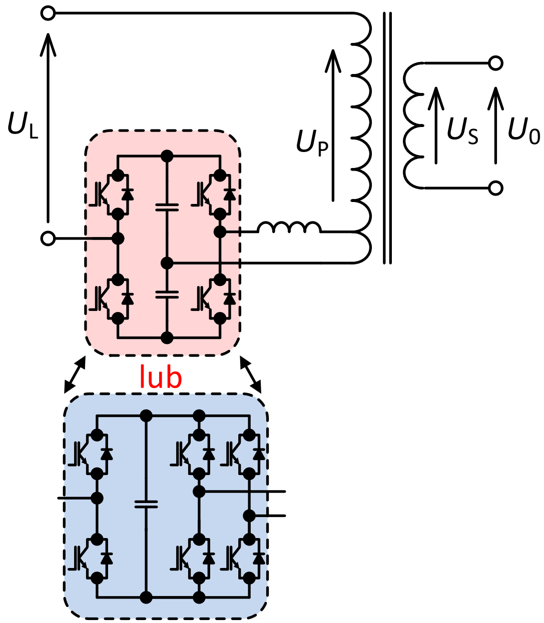
$$P_{IN} + P_C\cdot\eta_C = P_C + P_{Tr}$$

$$P_{OUT} = P_{Tr}\cdot\eta_{Tr} \;;\; k = P_C/P_{IN}$$

$$\Downarrow$$

$$P_{IN} + k\cdot P_{IN}\cdot\eta_C = k\cdot P_{IN} + P_{OUT}/\eta_{Tr}$$

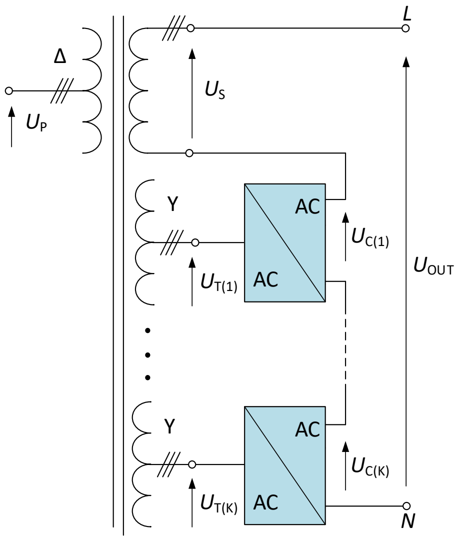
Example of a 1-phase DTH with one tap and regulation converter on the primary side



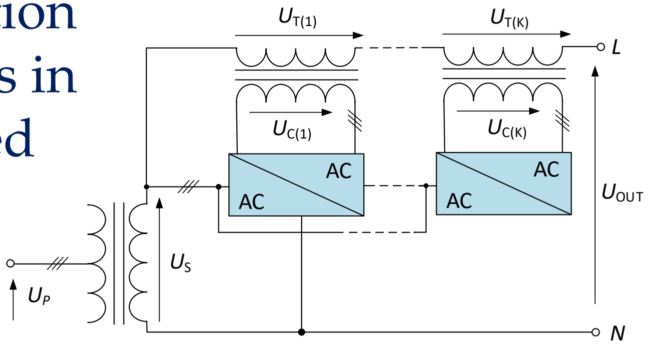
Circuit diagram

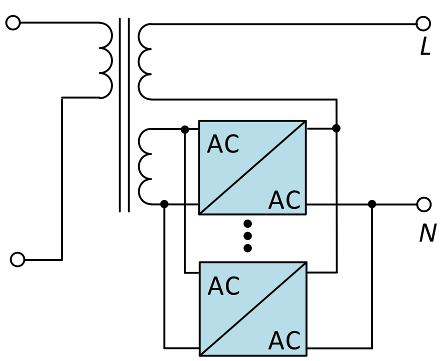
Design of a 50kVA prototype

Additional features of DTH

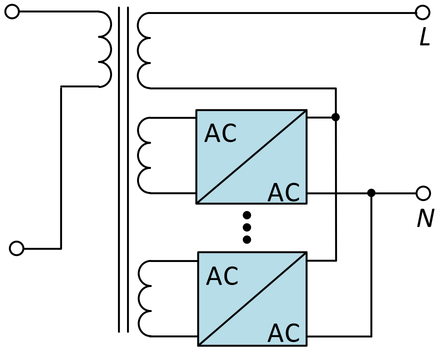


Examples of connection of converter modules in DTH with increased regulation range

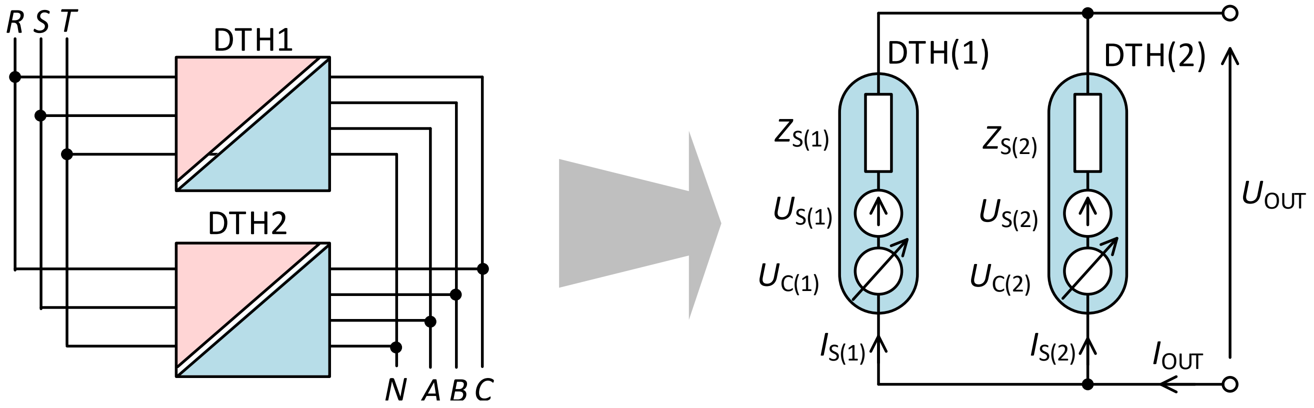




Examples of connection of converter modules in DTH with increased power outputs



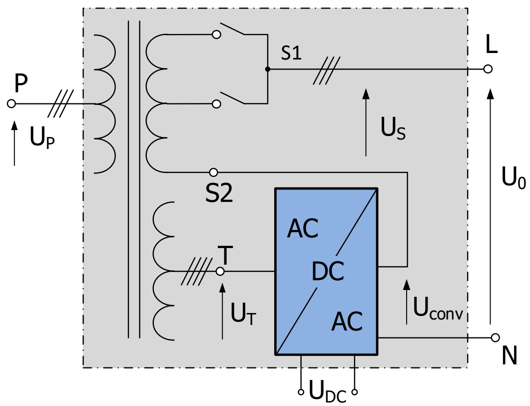
DTH parallel operation



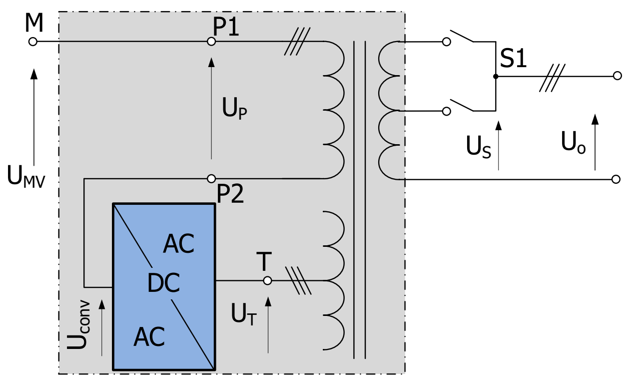
$$I_{S(1)} = I_{S(2)} = \frac{I_{OUT}}{2} \Leftrightarrow U_{C(1)} - U_{C(2)} = I_{OUT} \cdot \frac{Z_{S(1)} - Z_{S(2)}}{2} + U_{S(2)} - U_{S(1)}$$

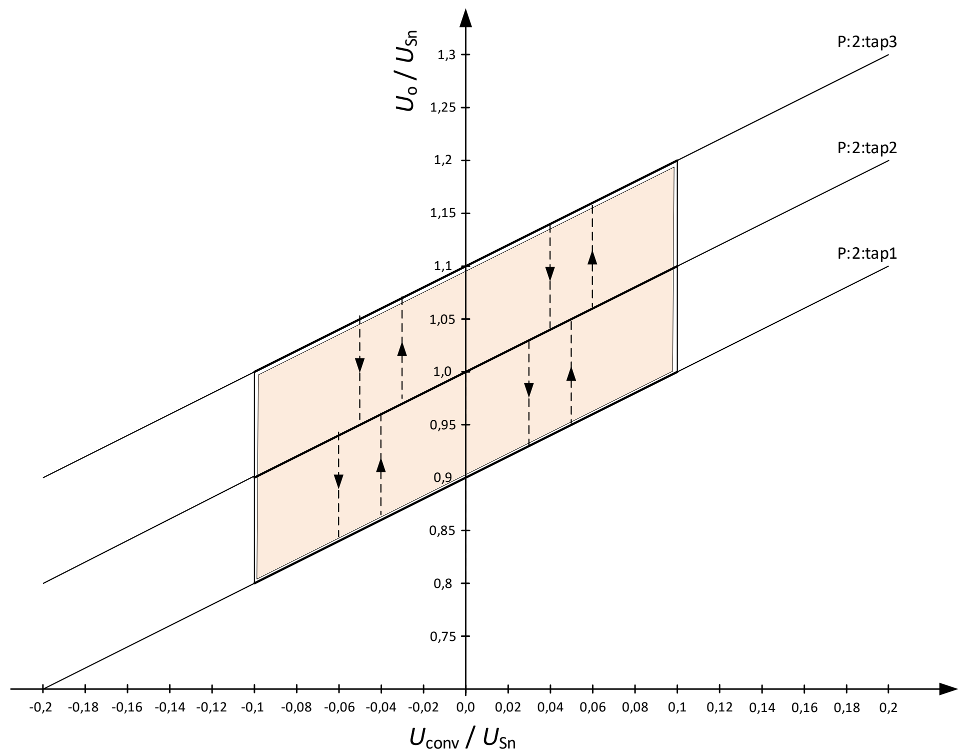
Multi-zone DTH

Systems with stepped-continuous regulation

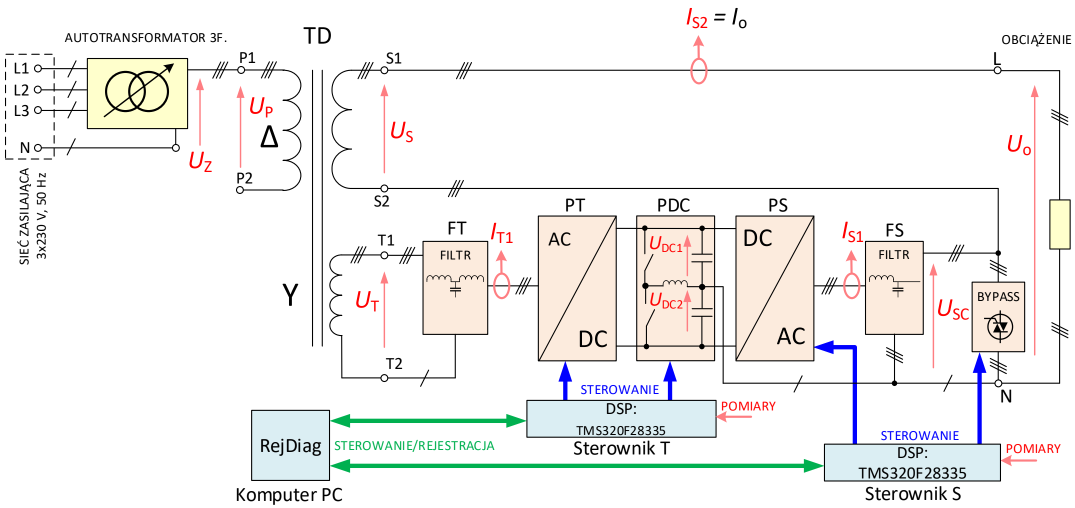


Characteristics of load voltage regulation as a function of the converter add voltage and the switched transformer tapping

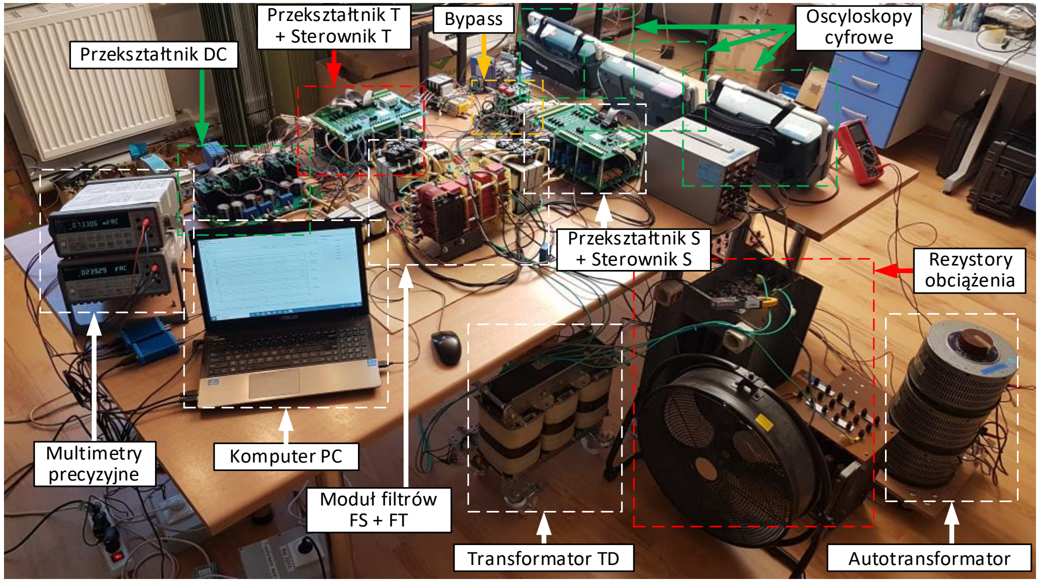




Lab stand for experimental testing of low-power DTH (10kVA)

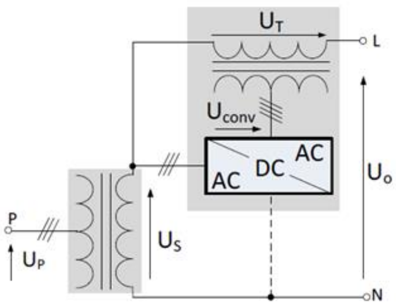


Block scheme

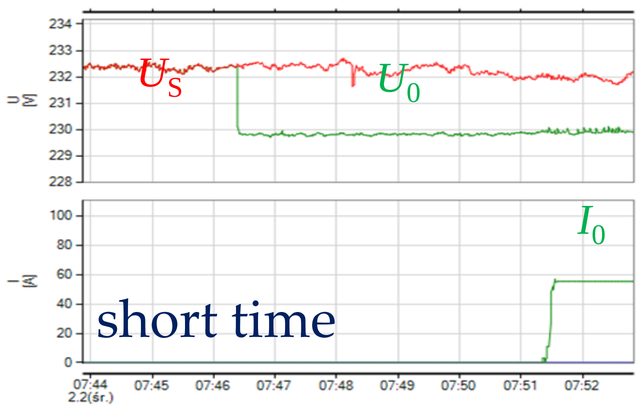


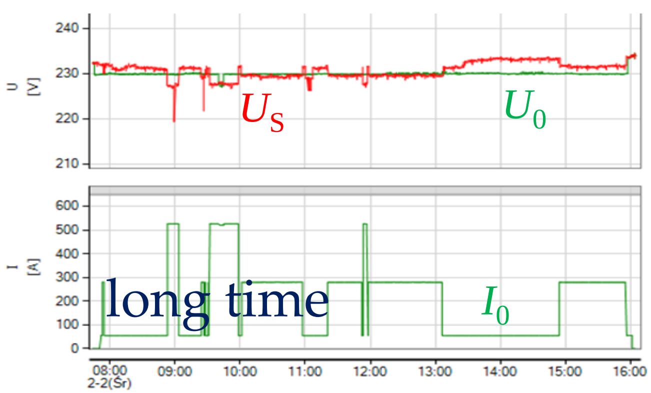
View of the stand

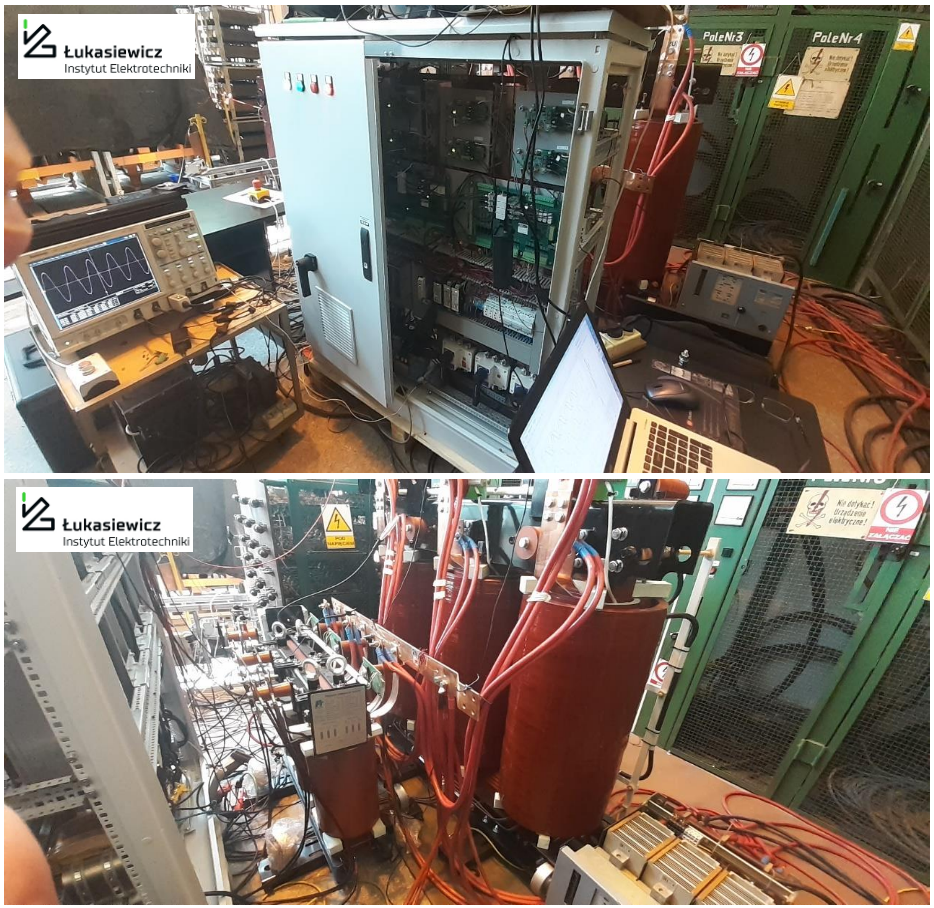
Prototype of a 630kVA HDT



Topology







View of the prototype

CONCLUSIONS

The investigated HDT systems with special switch, the so-called bypass, allow to adjust the voltage at high resolution at wide range, and with high dynamics, and increased reliability.

The HDT topologies provide additional functionality including: voltage symmetrization, compensation of higher voltage harmonics, or power flow control in ring systems.

Thanks to the dynamic and accurate voltage regulation offered by the HDT, energy systems operators gain greater control capabilities, together with the additional functionality of the device

An important advantage of the proposed HDT systems is its high efficiency, comparable with a classic transformer and a much lower cost than the power electronics transformer

Please ask questions and offer your own thoughts