The Highly Efficient And Reliable smart Transformer (HEART)

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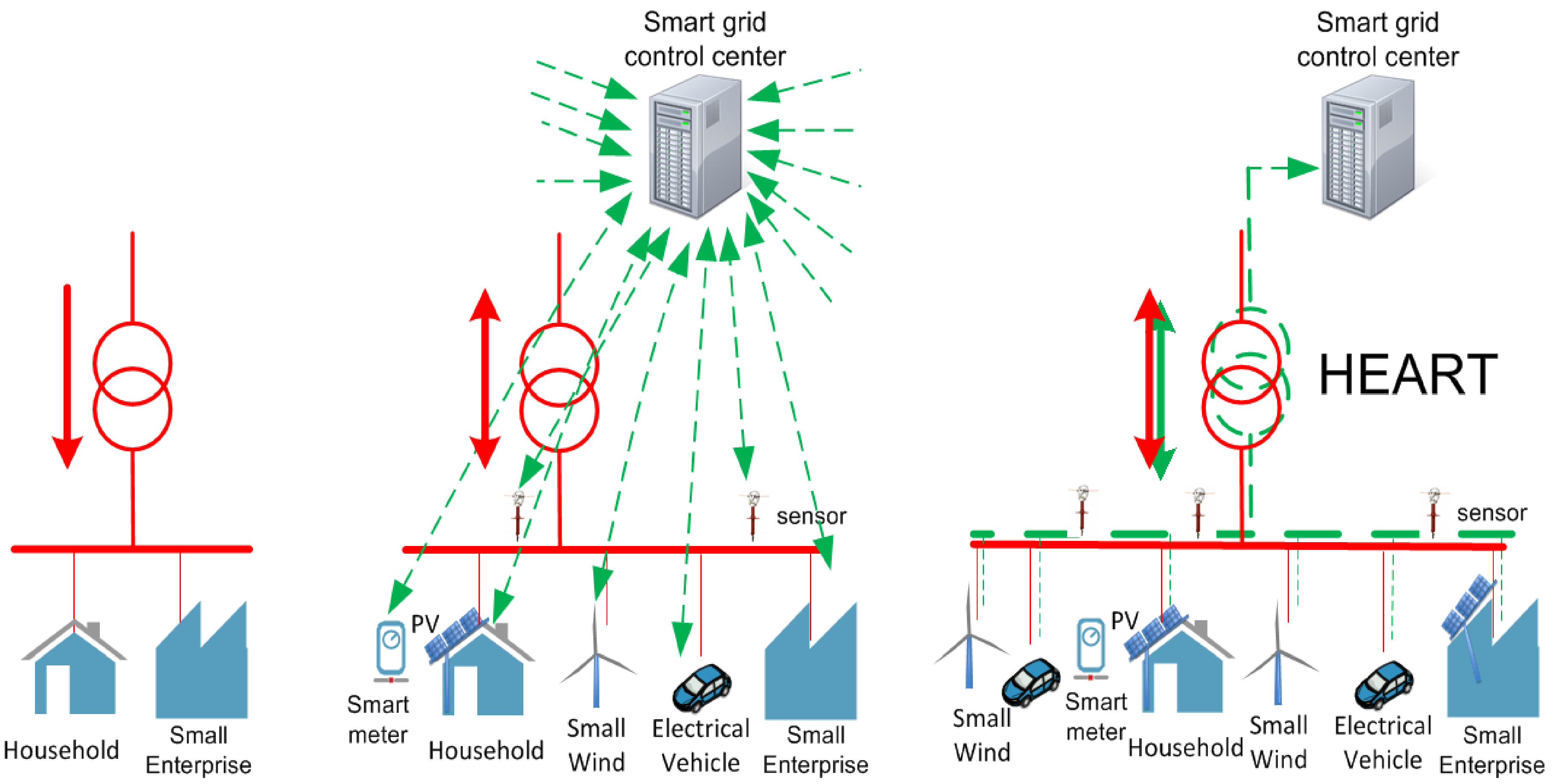
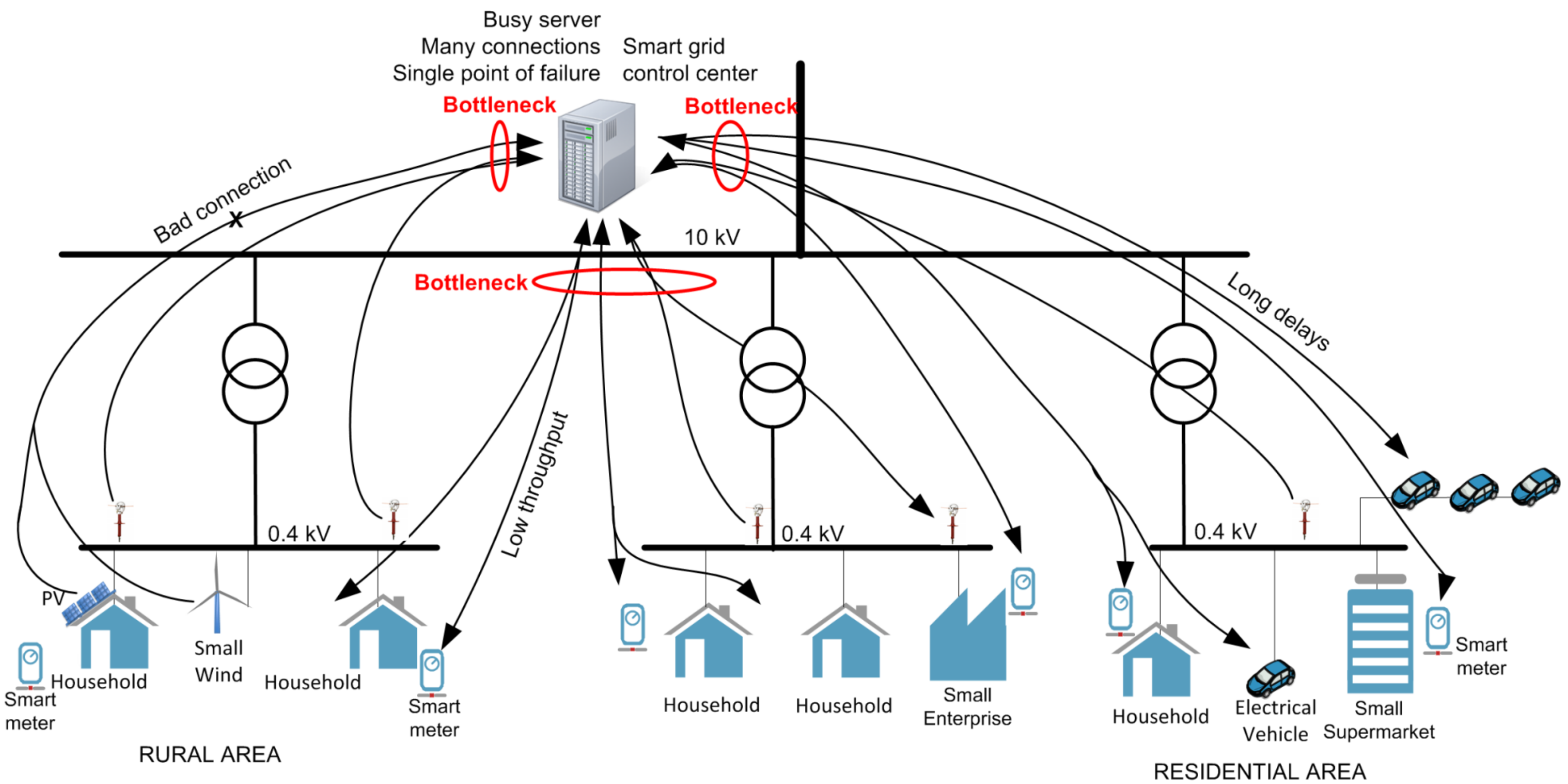
Outline

1. HEART Project
2. The Smart Transformer and the other intelligent solutions
3. Examples of ST functionalities in power system
4. ST architecture choice
5. Active thermal control
6. Implementation of HEART Project

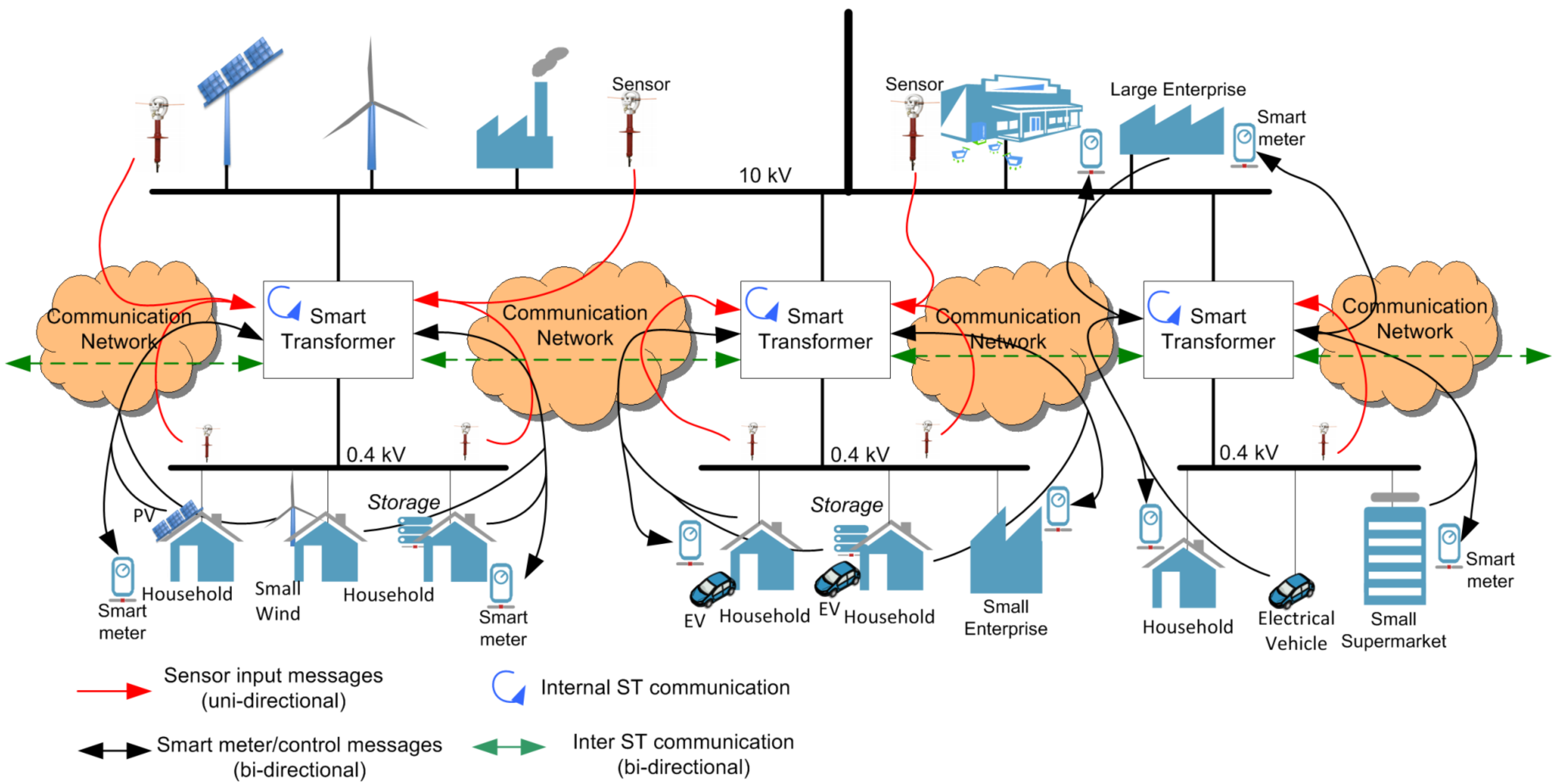
A new Heart for the Electric Distribution System



Critical issues of the future electric grid



A possible solution: the Smart Transformer



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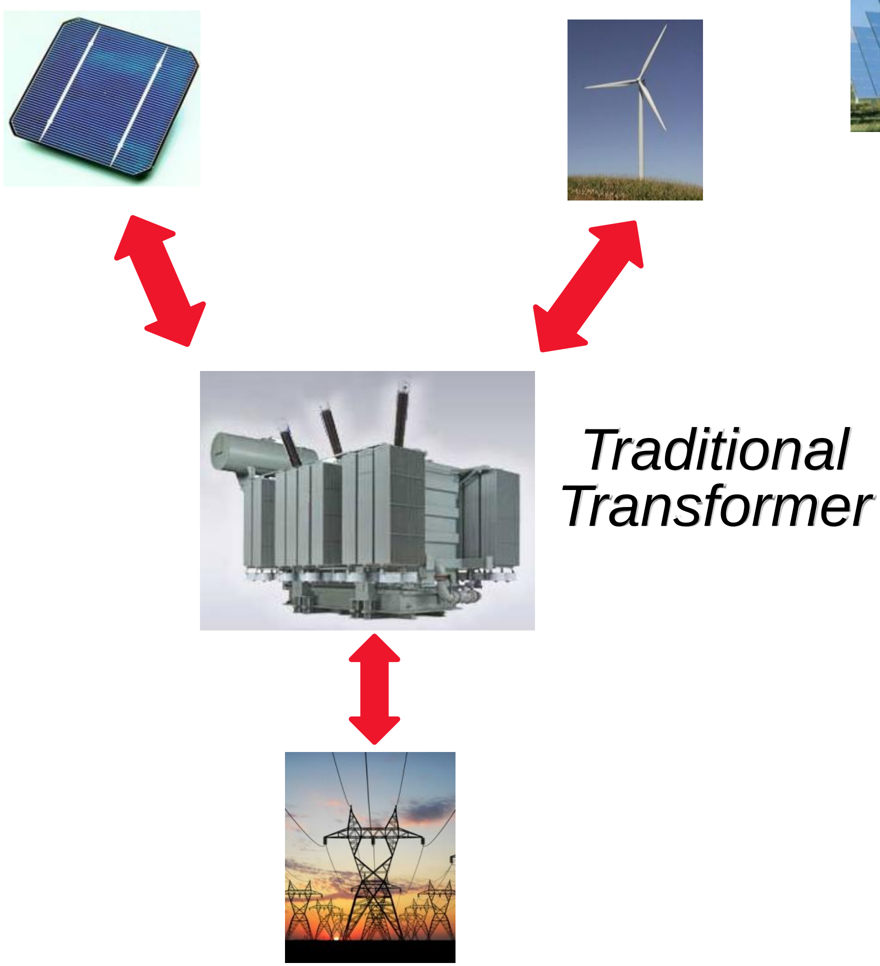
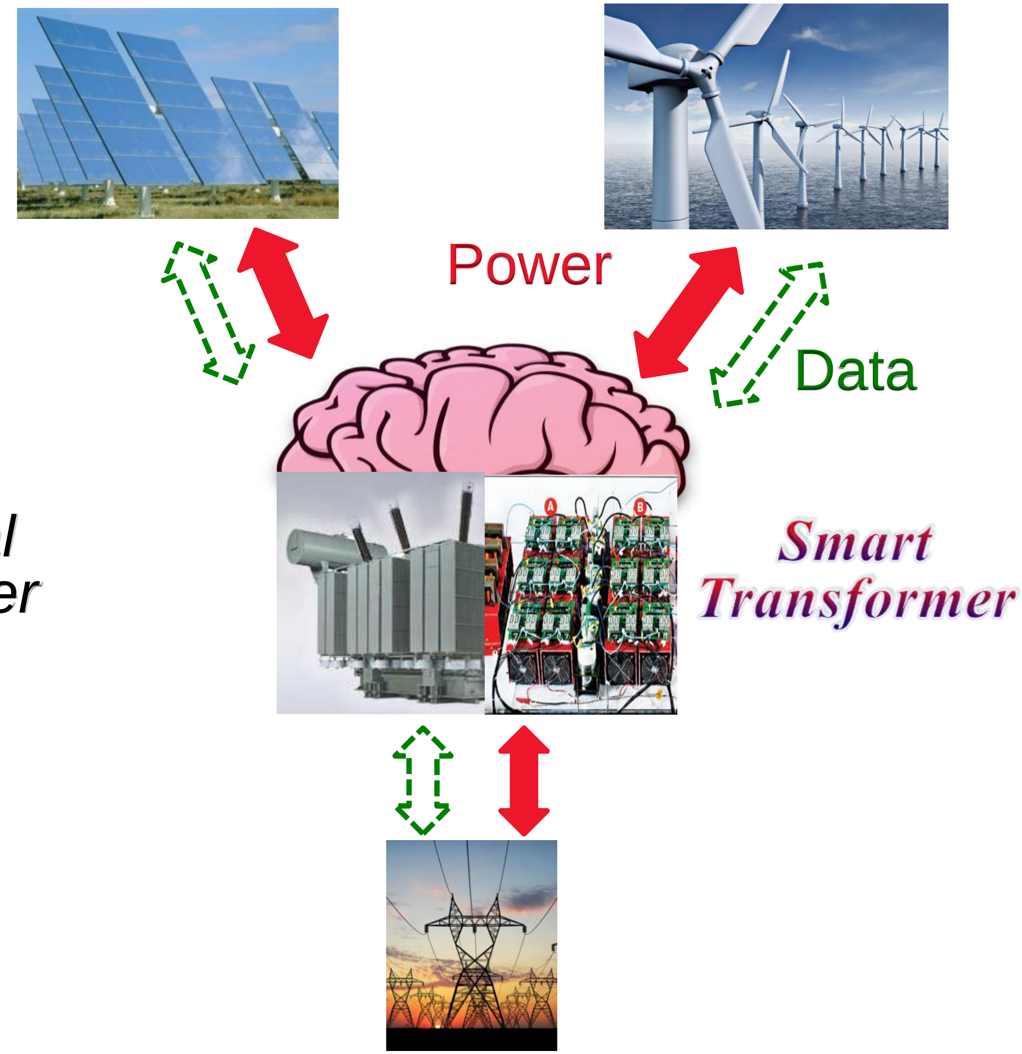
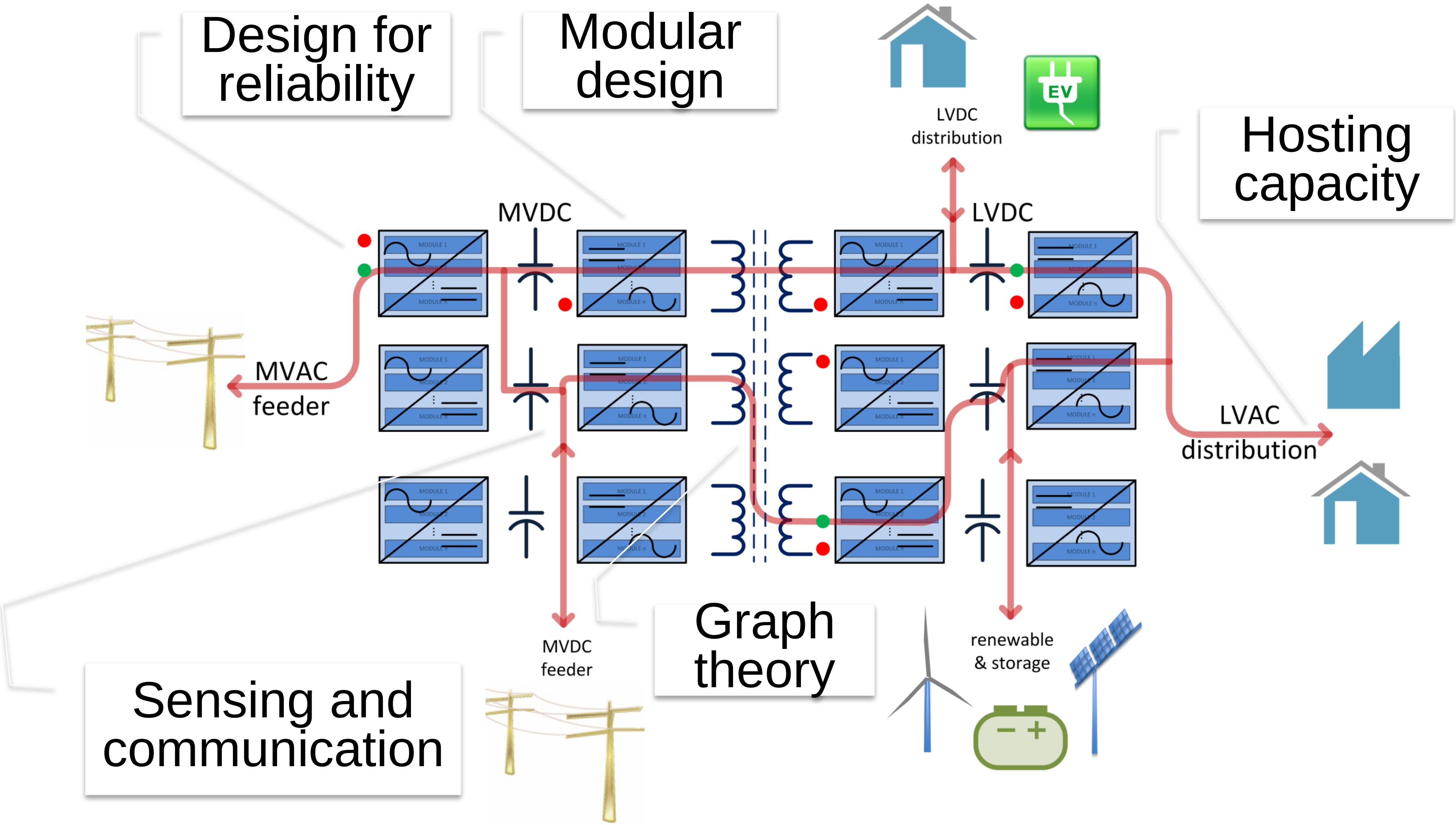
A new Heart for the Electric Distribution System

Limited penetration of renewables





Innovative idea and adopted methodologies



Approaches and methodologies

Hosting capability and reliability of the electric grid

- ✓ Benchmark the results respect to the smart grid
- ✓ If needed set a contigency plan

Design for reliability of the smart transformer

- ✓ ST lifetime estimation
- ✓ set a basis for on-line control of ST reliability

Modular design

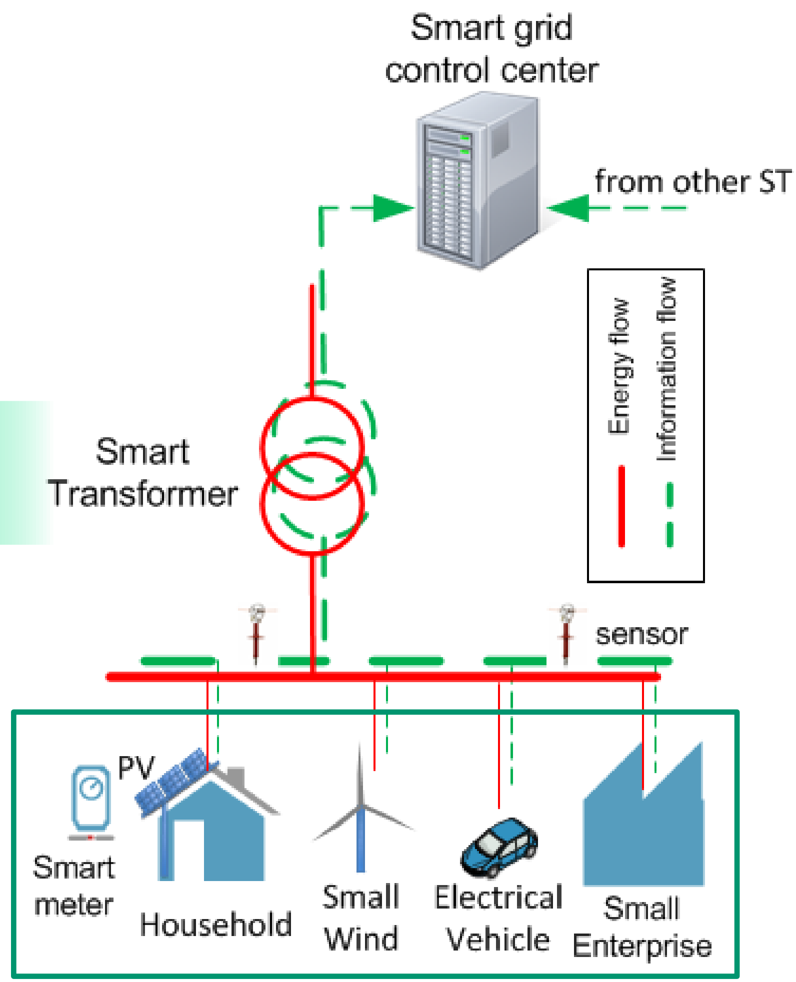
designing a modular ST architecture to allow routing the "packets of energy"

Active thermal control

find optimal paths (min losses and max reliability) for the "packets of energy"

Sensing and comunication

Junction temperature knowledge and real-time communication for routing the "packets of energy"



Expected results and potential contribution to the field

Smart grid	***Too decentralized*** ***Re-use of old concepts***	***New semi-decentralized managment***	***HEART is the solution !***
Smart transformer	***Many solutions taken from other applications***	***New energy router controlling on-line efficiency and reliability***	***HEART is competitive !***
sensors, actuators and communication	***No holistic solution***	***Actuate the energy routing***	***HEART is feasible !***

Low Voltage Grid Issues

- Unbalanced Power Flow
- Voltage Fluctuation
- Flicker
- Overloading
- Harmonics
- Voltage and Frequency Instability

On-Load Tap Changer (OLTC) Transformer

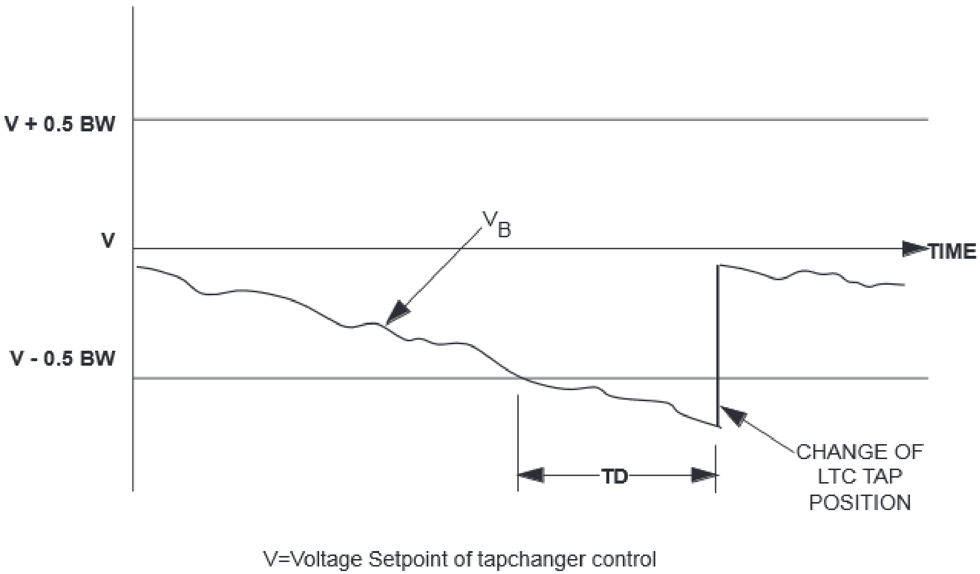


Figure 1 Illustration of the Interaction of Three Basic Control Settings

The OLTC modifies its voltage set point when the voltage profile goes down a predefined threshold. A time delay **TD** has set, avoiding the temporary voltage violations, operating only when the voltage violation is permanent.

In the Low Voltage grids the tolerance Bandwidth (BW) is commonly set within a range [1.5-3] V.

The working logic is the Line Drop Compensation, that controls the voltage in specific points of the grid. This represents a difficult task, due to the complexity of the grid, and the length of the lines.

Hybrid solution*

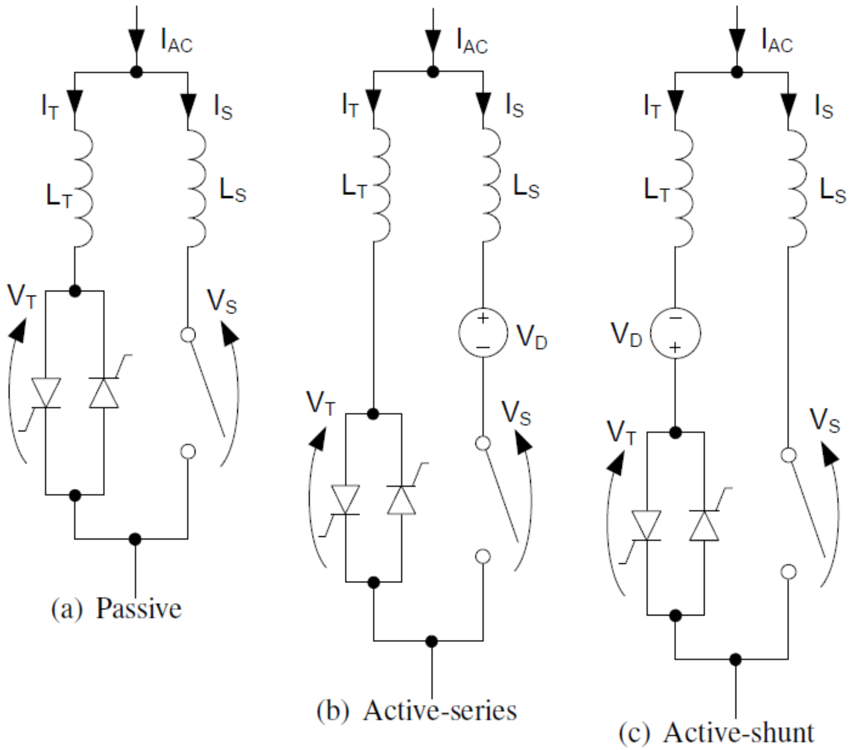


Fig. 1. Classification of hybrid OLTC schemes

a) **Passive type**: relies on the process of mechanical contact separation to drive current into an alternate path.

b) **Active-series type**: opposing a voltage source in series with the mechanical switch, the power is transferred to the semiconductor path. It avoid the switch under load.

c) **Active-shunt type**: the voltage source is placed in the semiconductor leg It cancels the thyristor forward voltage and drives a current equal to the load current into the semiconductor path. The switching current is zero and the arc-less operation is ensured.

* Rogers, D.J.; Green, T.C., "An Active-Shunt Diverter for On-load Tap Changers," Power Delivery, IEEE Transactions on , vol.28, no.2, pp.649,657, April 2013

Siemens solution*

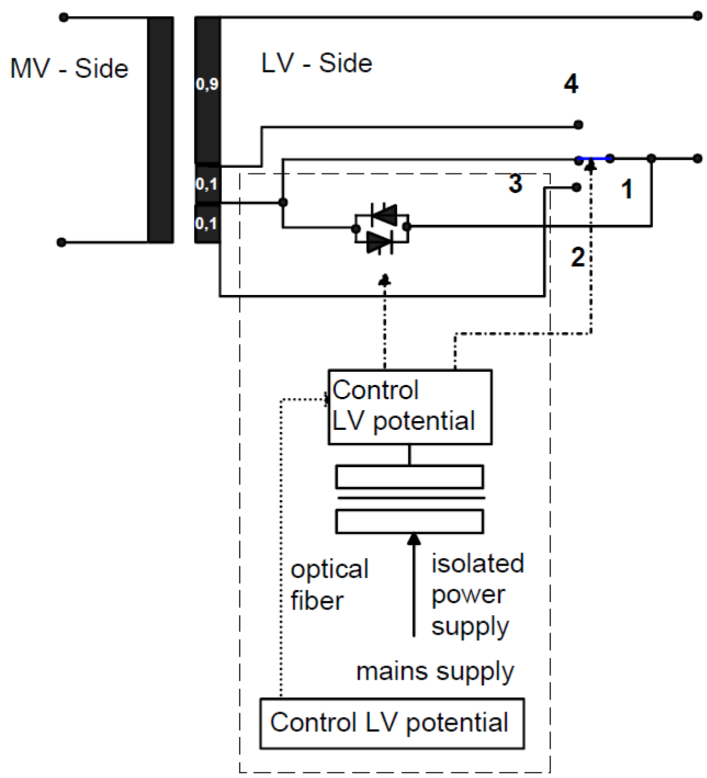


Figure 3: Principle of on-load tap changer

New concept: the solid-state relay acts to ensure continuous current flow by conducting the current during the mechanical switching operations.

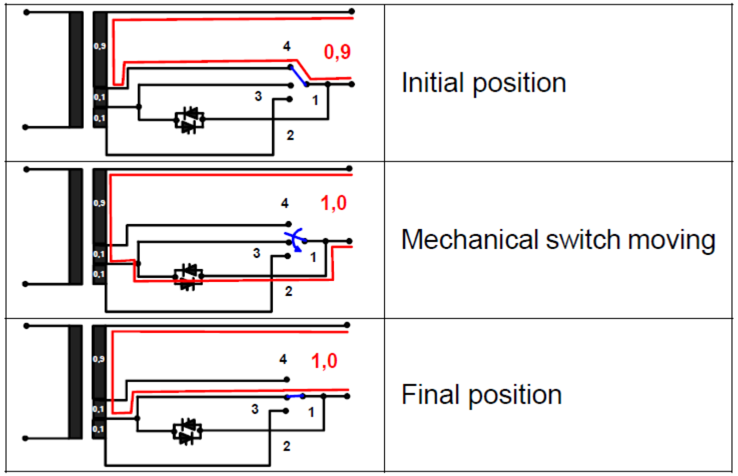
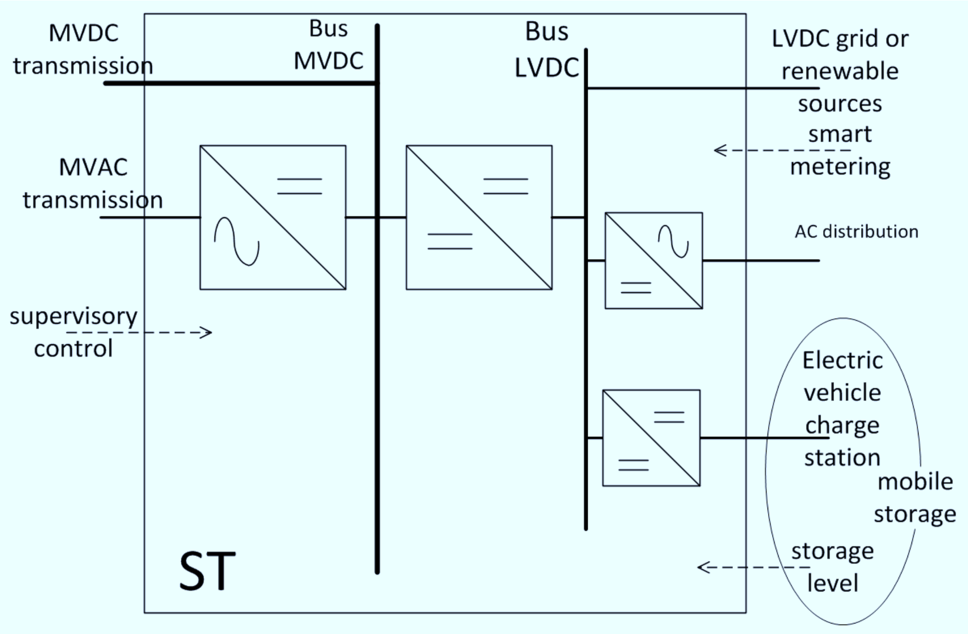


Figure 4: Commutation process

*G. Hipski, R. Schmid, R. Maier, K. Handt, G. Buchgraber, "Distribution Transformers – ready for the smart grid", 21st International Conference on Electricity Distribution, CIRED, Frankfurt, 6-9 June 2011.

Capabilities of the Smart Transformer

- Power quality enhancement: disturbance isolation, harmonics and transients
- DC-connectivity: future MVDC, low voltage DC grids and renewable energy
- Fault reclosing coordination
- Energy storage: Electric vehicle batteries (challenges and opportunities)



Comparison among transformers*

TABLE I. OVERVIEW OF THE SUPPORT FUNCTIONS FROM TRANSFORMERS

	Traditional transformer with off load tap changer	Traditional transformer with on load tap changer	ST
Reducing grid losses	partly	yes	yes
Improving EV/PV hosting capacity	partly	partly	yes
Eliminating voltage harmonic	no	no	yes
Reducing voltage unbalance	partly	partly	yes
Relieving flicker	no	no	yes
Relieving voltage fluctuation (duration > 1minute)	no	partly	yes
Fault isolation	no	no	yes
Supply reliability	no	no	yes

*Shaojun Huang; Pillai, Jayakrishnan R.; Liserre, Marco; Bak-Jensen, Birgitte, "Improving photovoltaic and electric vehicle penetration in distribution grids with smart transformer," Innovative Smart Grid Technologies Europe (ISGT EUROPE), 2013 4th IEEE/PES , vol., no., pp.1,5, 6-9 Oct. 2013

Improving EVs and PVs Hosting Capacity*

The smart transformer perform better voltage regulation and support higher EV and PV penetration levels in the local distribution grids, when compared to the conventional transformer with OLTC.

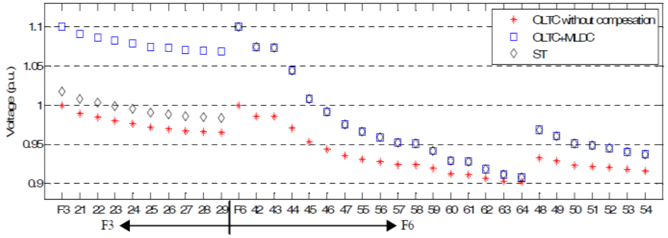


Figure 3: voltage profiles of scenario 1 (with only EV connected)

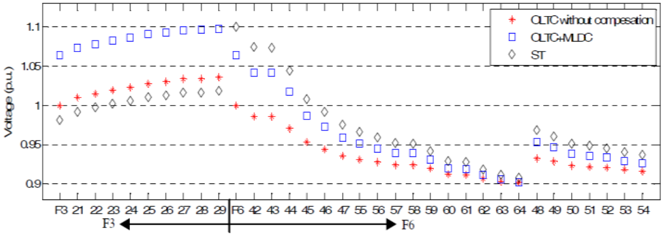


Figure 4: voltage profiles of scenario 2 (with EV+PV connected)

$$J_n(V_{se}) = (V_{nom} - V_{n,\max})^2 + (V_{nom} - V_{n,\min})^2$$

	Feeder 3(PV penetration level of 27HH)	Feeder 6(EV penetration level of 39HH)
Traditional transformer+ OLTC (no compensation)	64.8%	10.7%
Traditional transformer + OLTC (MLDC method)	64.8%	20.6%
ST	64.8%	25.5%

*Shaojun Huang; Pillai, Jayakrishnan R.; Liserre, Marco; Bak-Jensen, Birgitte, "Improving photovoltaic and electric vehicle penetration in distribution grids with smart transformer," Innovative Smart Grid Technologies Europe (ISGT EUROPE), 2013 4th IEEE/PES , vol., no., pp.1,5, 6-9 Oct. 2013

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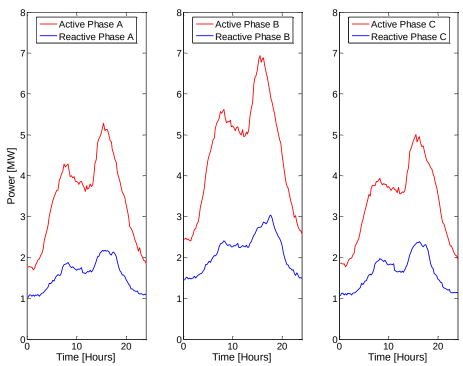
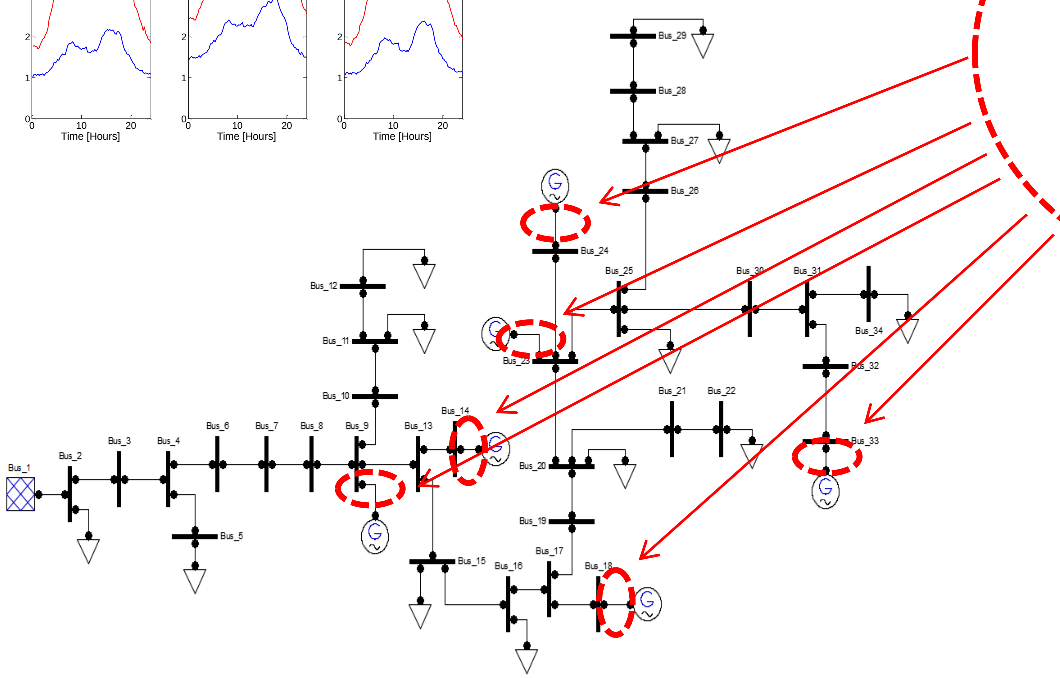
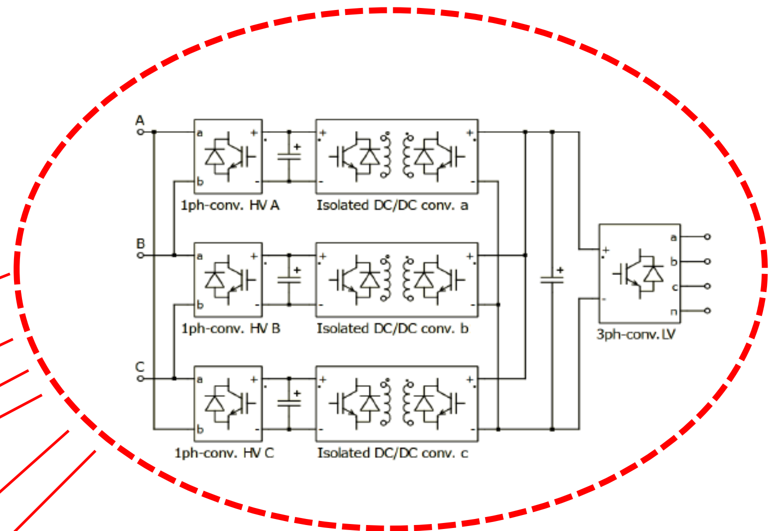
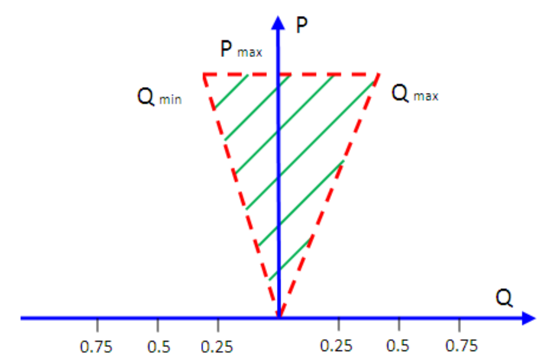
Voltage Control and Current Congestion Management*

Total load









*G. De Carne, M. Liserre, M. Paolone, K. Christakou, "Voltage Control and Current Congestion Management in Distribution Grdis by means of a Smart Transformer", submitted to ISIE 2014, 1-4 June, Istanbul.

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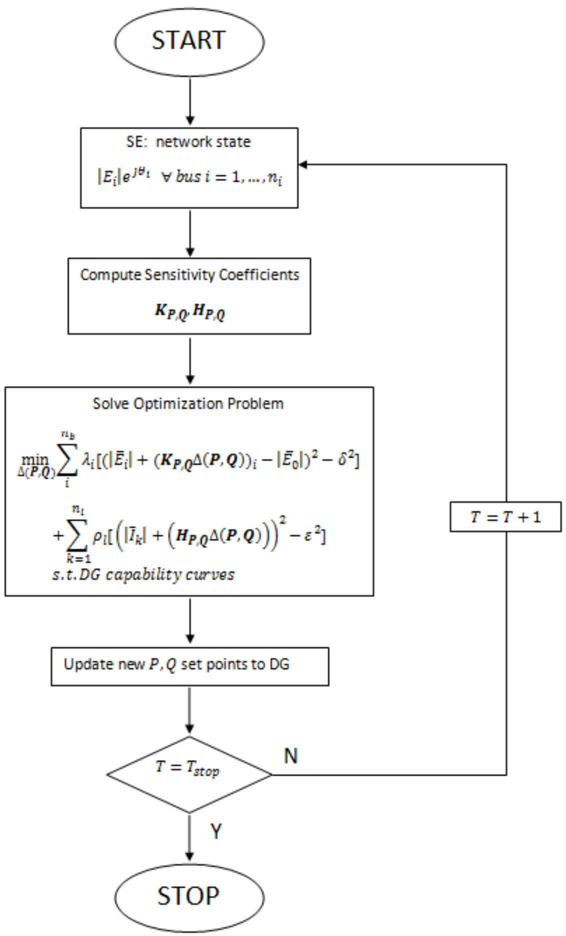
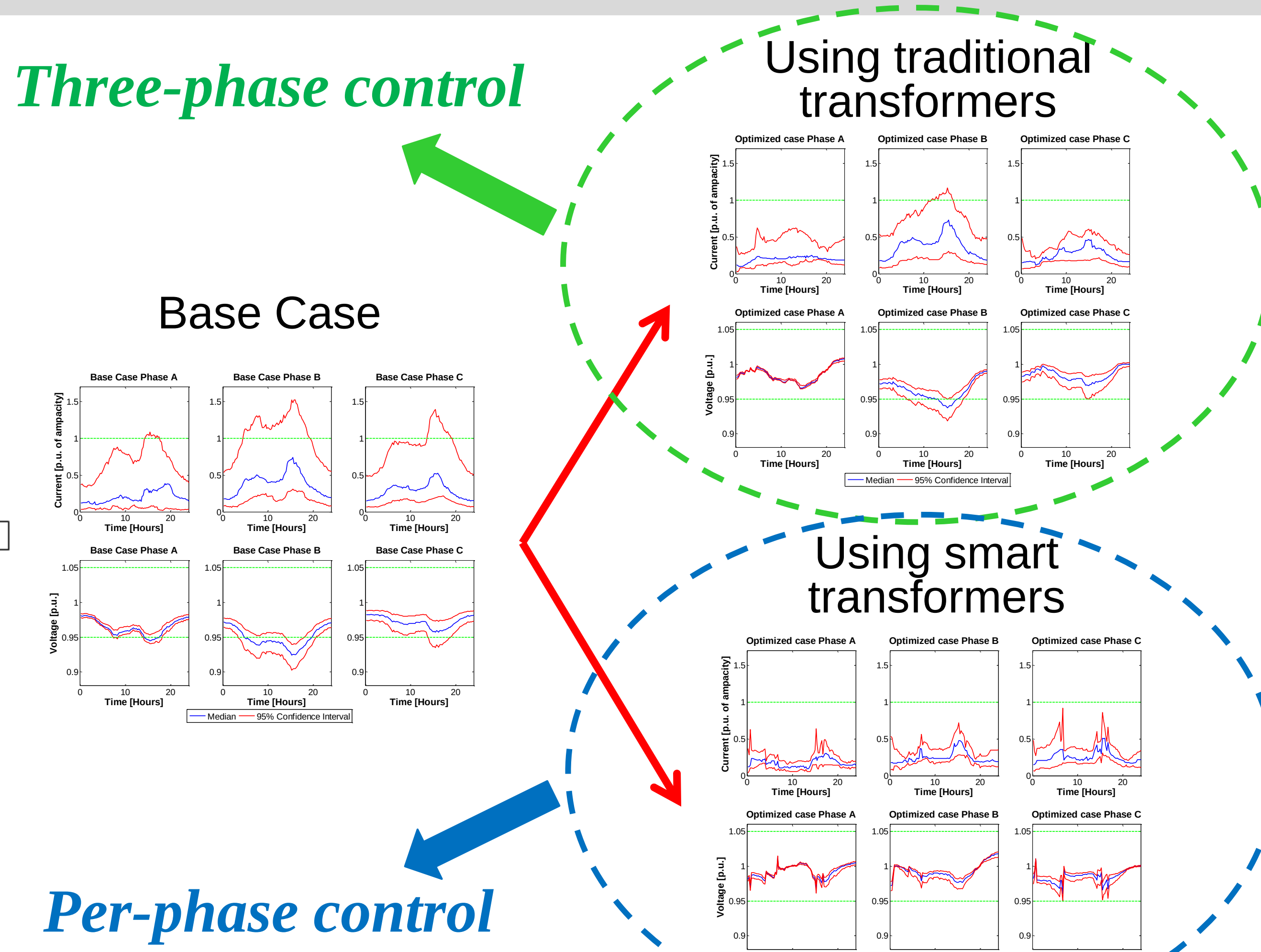
Voltage Control and Current Congestion Management*





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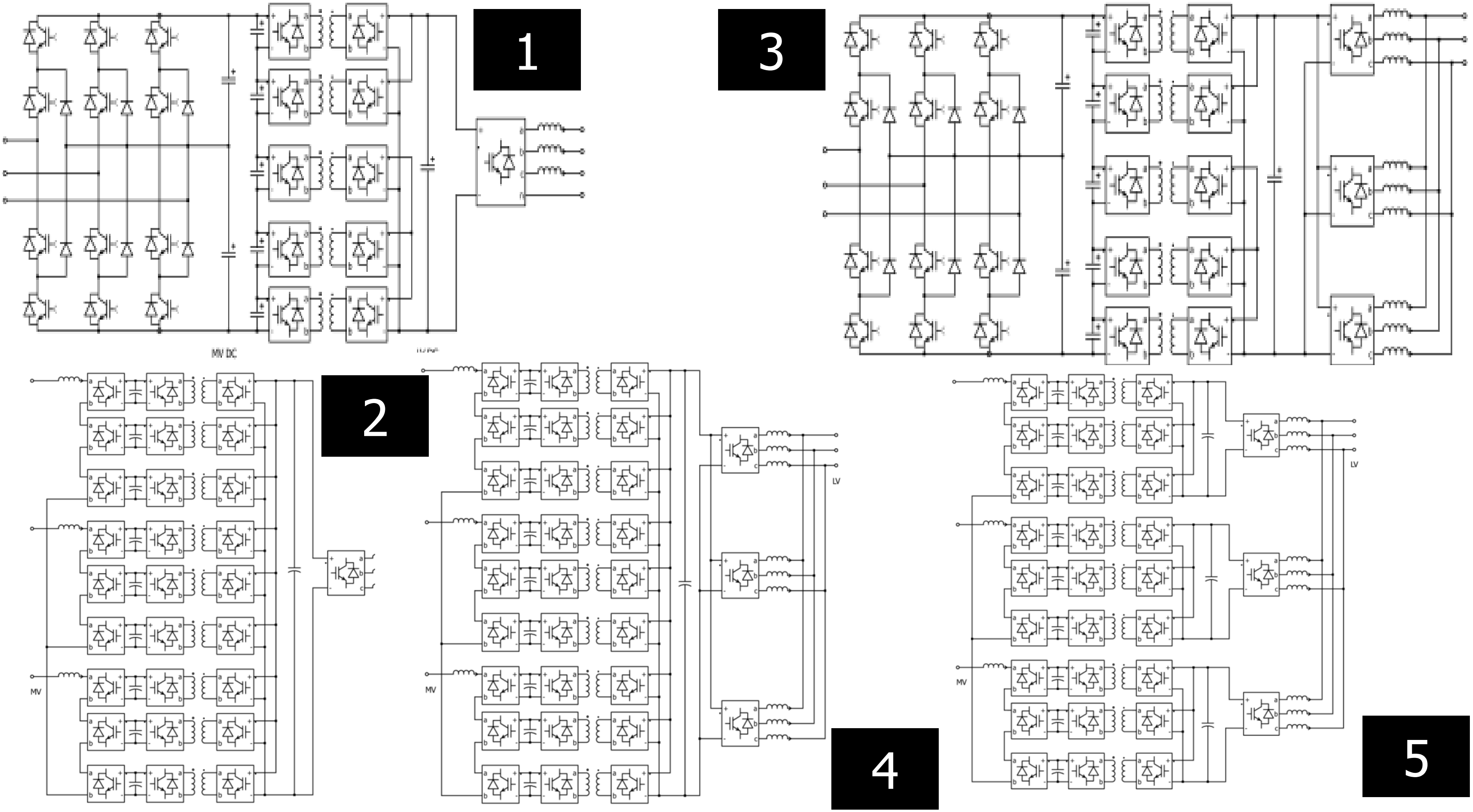
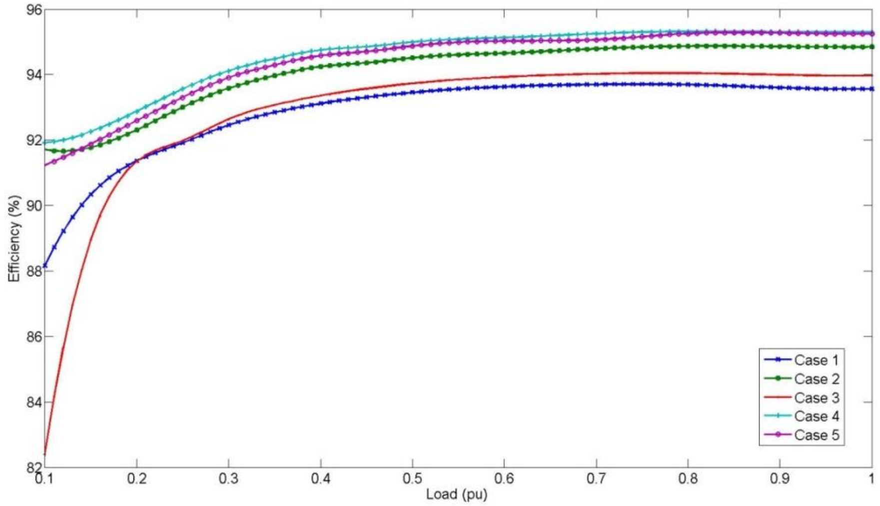
ST Architecture

- ✓ One stage (AC-MV/AC-LV)/ Two stage (AC-MV/DC-MV /AC-LV)
  - ✓ Reduced component counts
  - ✓ Does not allow integration of either MV/LV DC network
  - ✓ disturbances on one side may also affect the other side
- ✓ Three Stage (AC-MV/DC-MV/DC-LV/AC-LV)
  - ✓ DC-links on both sides and performing three stages of conversion
  - ✓ Allows direct integration of renewable DC sources
  - ✓ Modularity

Several architectures



Comparison



- Cascaded H-bridge seems to be the best solution but it does not allow MVDC connectivity
- MVDC connectivity is at the expense of efficiency

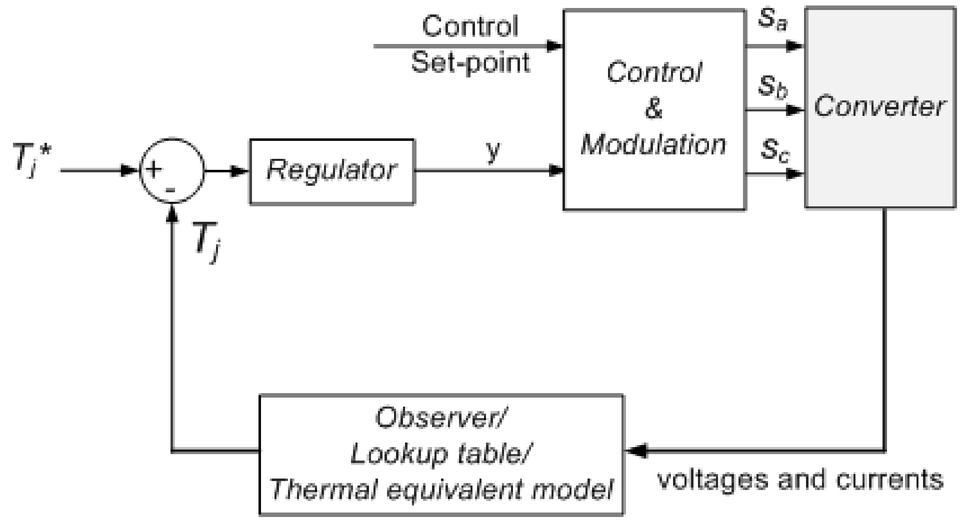
Case	Modularity	Efficiency	Reliability	Cost	DC connectivity
1	-	-	++	++	MV and LV
2	+	+	+	+	LV
3	+	-	++	++	MV and LV
4	++	++	+	+	LV
5	++	++	+	+	LV

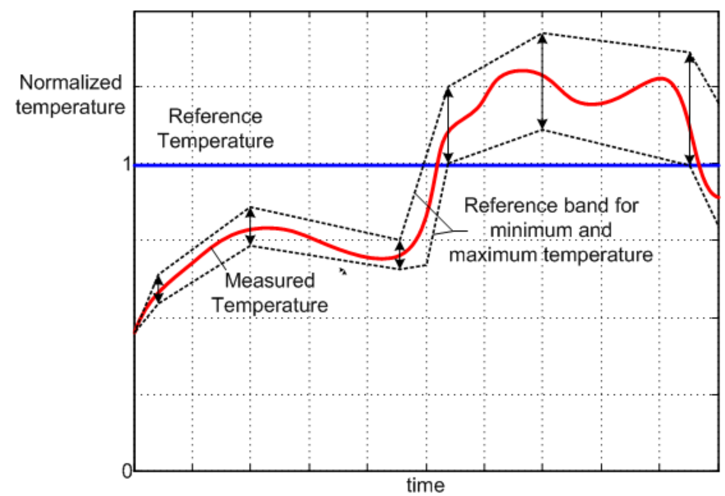
Topology Impact on the Distribution System Enhancement

	NPC					CHB				
	LV Common DC link			LV Separate DC links		LV Common DC link			LV Separate DC links	
	One Inverter	Multi-Inverter		Multi-Inverter		One Inverter	Multi-Inverter		Multi-Inverter	
	One Feeder	Each Phase	Each Feeder	Each Phase	Each Feeder	One Feeder	Each Phase	Each Feeder	Each Phase	Each Feeder
Unbalanced Voltages Control	+	++	++	++	++	+	++	++	++	++
Voltage Variations & Flicker Compensation	-	+	++	++	++	+	+	++	++	++
Harmonics Pollution Reduction	++	++	+	+	+	++	++	+	+	+
Unbalanced Power Flow Control	-	+	++	+	+	-	+	+	-	-
Limit EVs Impact and Improve Hosting Capacity	-	+	++	+	++	-	+	++	-	-
Losses Reduction	+	++	++	++	++	+	++	++	++	++
MV DC link accessibility	+	+	+	+	+	-	-	-	-	-
LV DC link accessibility	+	+	+	++	++	+	+	+	++	++

Active Thermal Control

- High temperatures, humidity, shocks and vibration reduce the lifetime of a power module as well as thermal cycling
- Direct measurement of the junction temperature is problematic, which calls for observers, models or lookup tables
- Wear out changes thermal behavior over time





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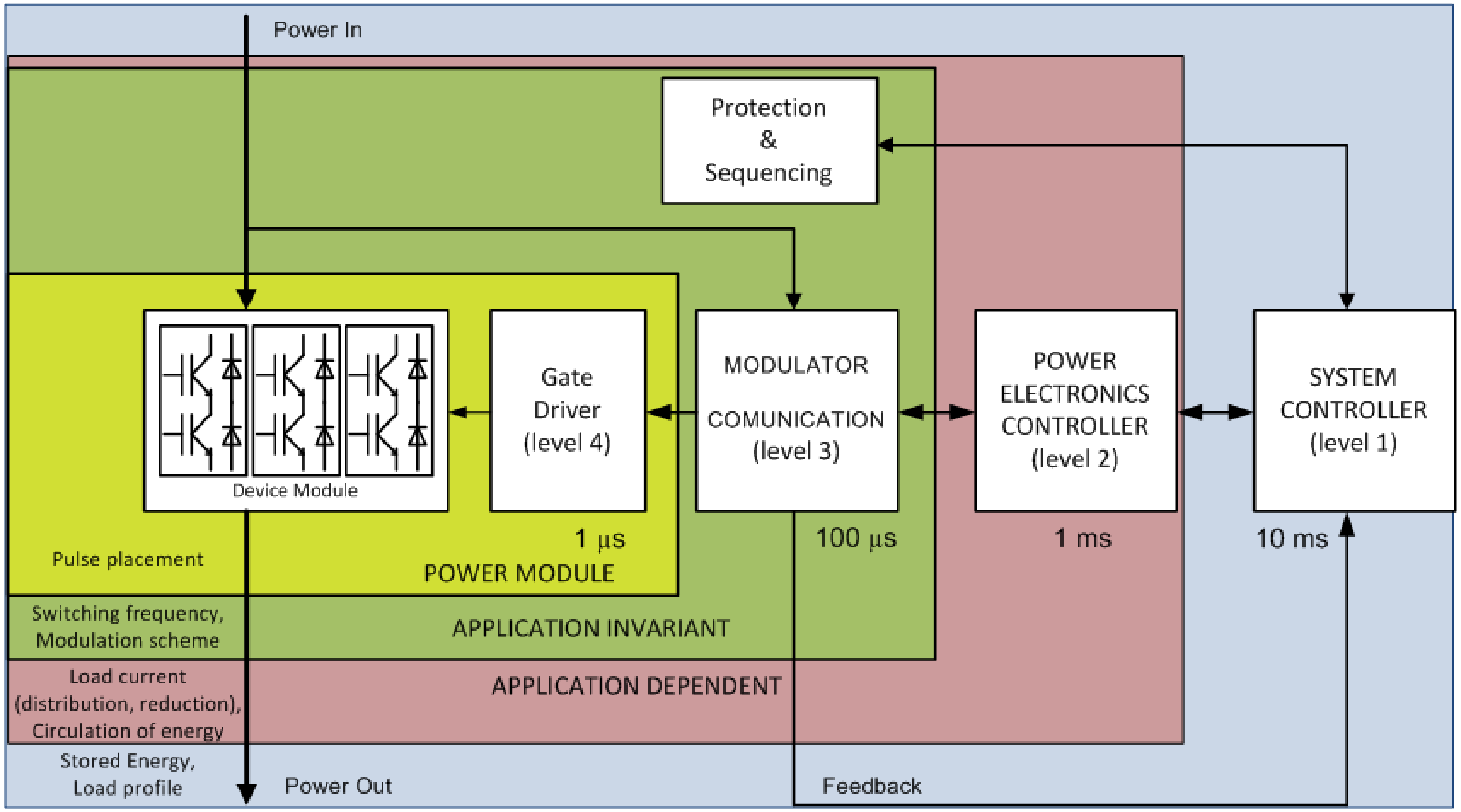
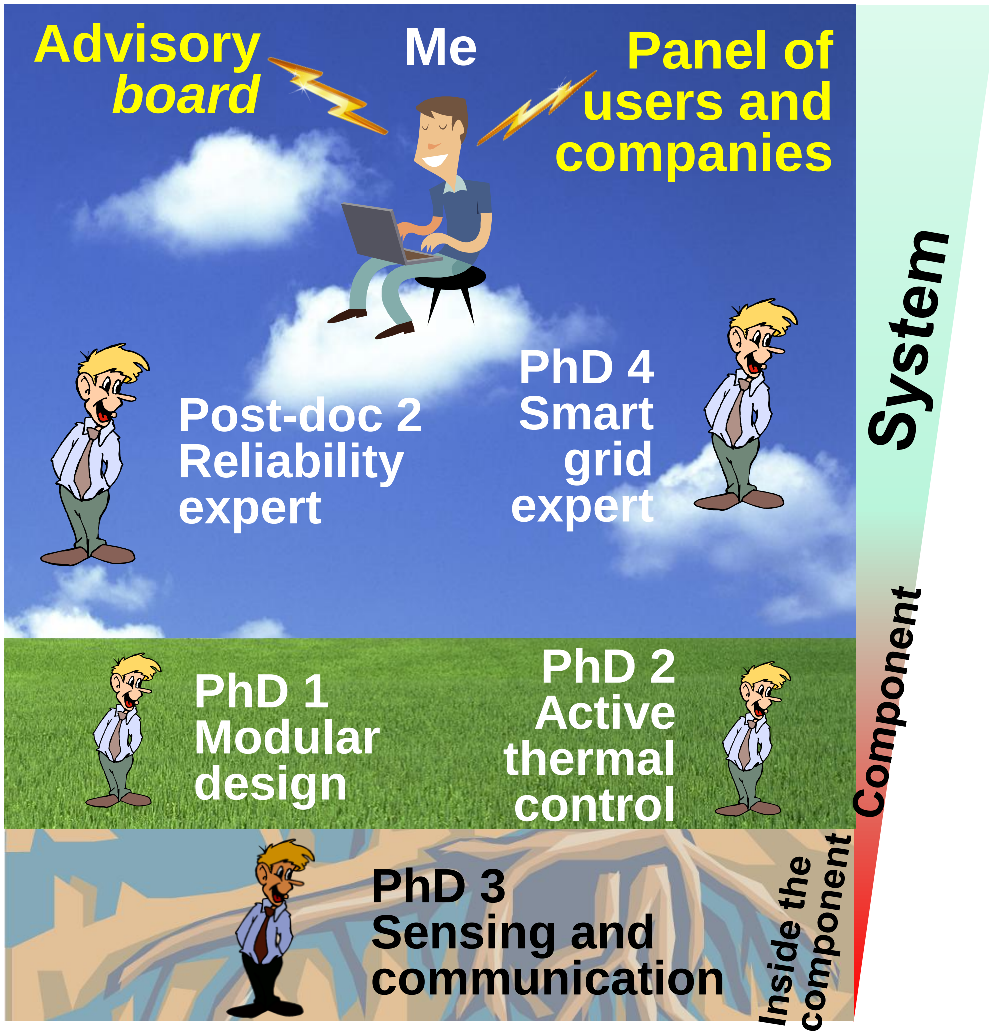
Active Thermal Control



The research team



The project will be carried out in cooperation with

AALBORG UNIVERSITY
Department of ENERGY TECHNOLOGY
E.T.

CORPE

A Laboratory will be developed to carry out the project

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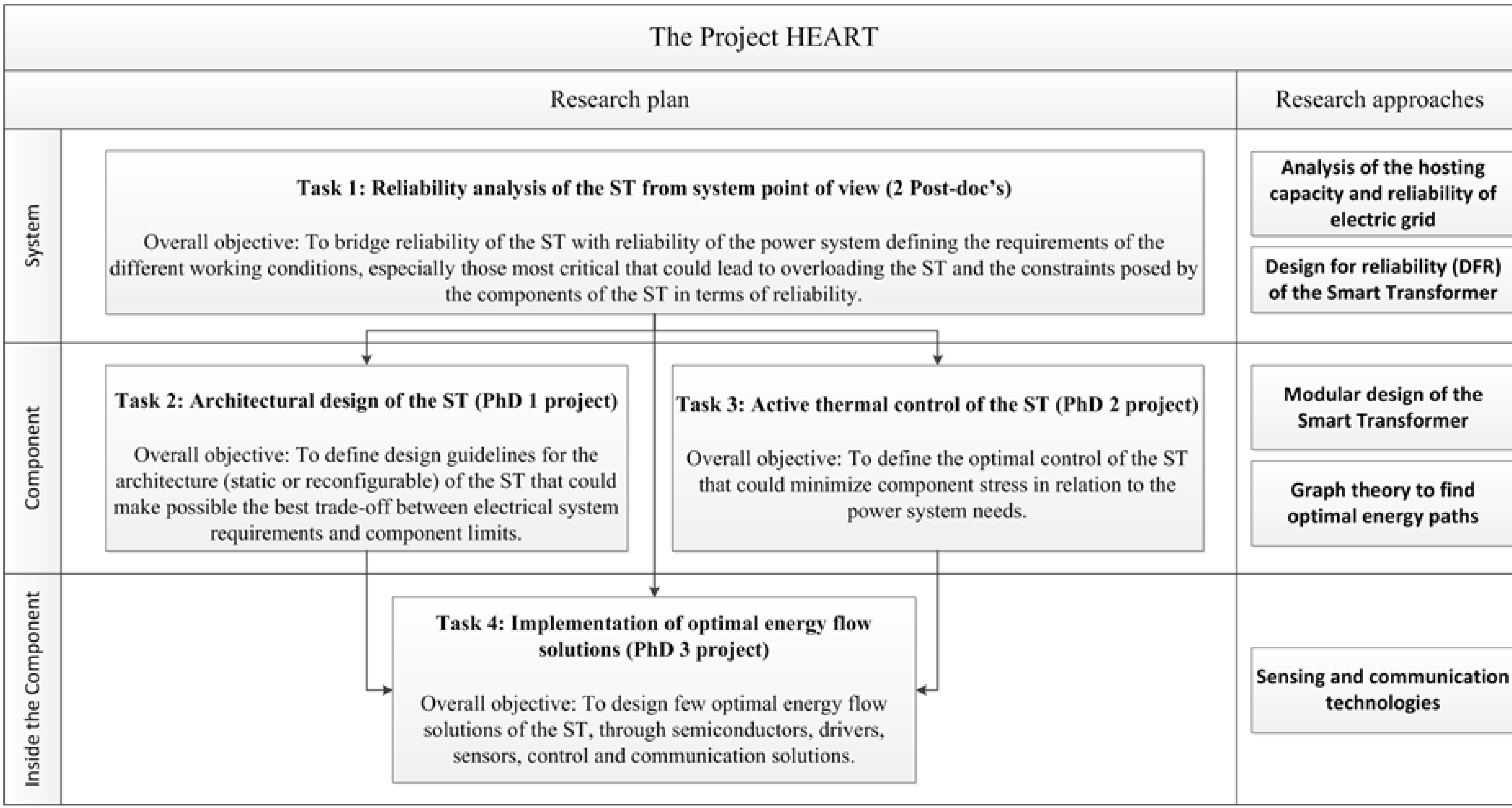
Plan of activities



Timetable

Tasks		Year 1				Year 2				Year 3				Year 4				Year 5			
0	**Project coordination**																				
	Project homepage																				
	PhD courses (1-week international)			X						X									X		
	Public seminars and open-source software				X						X										X
	External review (IAB and PUC)										X										X
1.	**Reliability analysis of the ST from system point of view**																				
1.1	Analysis of ST features for electric distribution (PD1)				X						X										
1.2	Assessment of the hosting capacity and reliability of the electric distribution (PD2)										X										X
M	Report				*						#										#
	Publications (number)												2								2
2	**Architectural design of the ST**																				
2.1	Study of the ST's architectures (1st year PhD1)							X													
2.2	Comparison of the power converters to be used in the ST (2nd year PhD1)											X									
2.3	Design of ST hardware (3rd year PhD1)															X					
M	Report															°					
	Publications (number)							1				2				3					
3.	**Active thermal control of the ST**																				
3.1	Analysis of the ST operation modes in terms of thermal stress (1st year PhD2)							X													
3.2	Assessment of critical operation modes and their impact on the ST's reliability (2nd year PhD2)											X									
3.3	Design of ST software (3rd year PhD2)															X					
M	Report															°					
	Publications (number)							1				2				3					
4.	**Implementation of optimal energy flow solutions**																				
4.1	Semiconductors devices and their intelligent drivers (1st year PhD3)											X									
4.2	Sensors (2nd year PhD3)															X					
4.4	Communication (3rd year PhD3)																			X	
M	Report																				
	Publications (number)											1				2				3	
Intermediate research stages	Analysis of benefit/necessities/cost of the ST in present/future distribution grids				→																
	Validation of energy routing impact on efficiency and reliability										→										
	Definition of optimal energy path problem with graph theory															→					
	Realization of two small prototypes for experimental validation of energy routing approach																		→		
	Test of prototypes in real electric grid scenario using Real Time Digital Simulator (RTDS)																				→
Human resources involvement (light blue = minimum, dark blue = maximum)																					

** the report is the starting point of PhD1 and PhD2 # the report is used for external review ° the report is starting point of PhD3*

IAB – International Advisory Board, PUC – Panel of Users and Companies