Optimal reactive power control of distributed wind power plants for loss minimization in medium voltage networks

Kaushik Das, Theofanis Sofianopoulos, Müfit Altin, Anca D Hansen, Poul E Sørensen
Department of Wind Energy, Technical University of Denmark (DTU)
Risø, Denmark

Gitte Wad Thybo
ENIIG Forsyning A/S

EDPGTS11 – Optimal Integration of Variable Renewable Generation into Power Systems – Coordination of measures at TSO and DSO level

IEEE PES Power & Energy Society®

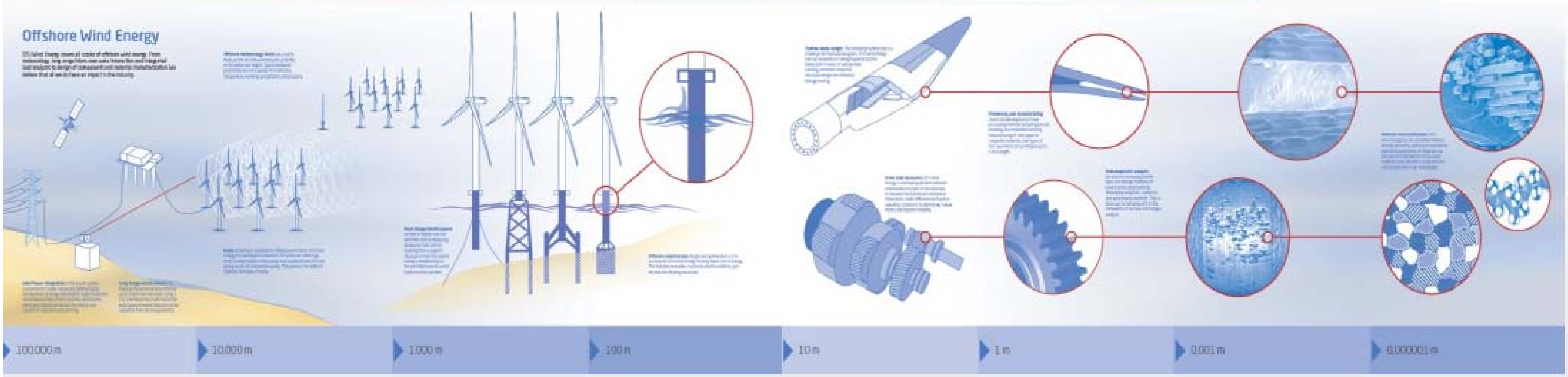
IEEE

237 staff members:

- **150 academic staff members**
- **40PhD students**

DTU Wind Energy

- **Resource Assessment Modelling**
- **Meteorology and Remote Sensing**
- **Integration and Planning**
- **Loads and Control**
- **Fluid Mechanics**
- **Aerodynamic Design**
- **Structures and Component Design**
- **Test and Measurem.**
- **Material Science & Characterization**
- **Composites & Materials Mechanics**



Siting and integration

Offshore wind energy

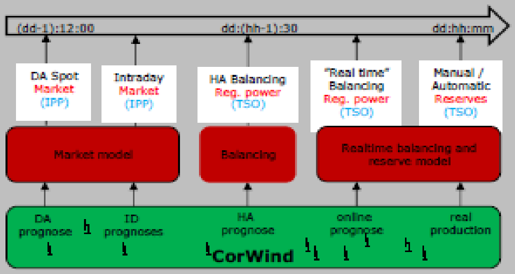
Wind turbine technology

Education and teaching

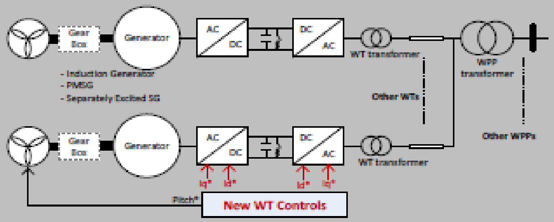
Research based consultancy and tests

INP – Integration and Planning

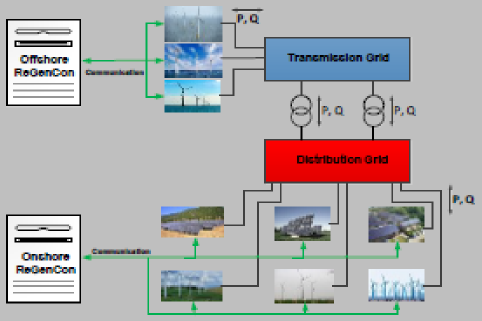
Variability
Balancing
Reserves



Modelling
Control



Ancillary
Services



Research themes

Integration and control of wind energy in power systems

- Power system – variability, balancing, reserves, stability
- Wind power plants – dynamic modelling, ancillary service
- Electrical design, controls and test facilities

Offshore wind power plants and grids

- Wind power plant and grid concepts
- Electrical infrastructure design
- Controls and operation

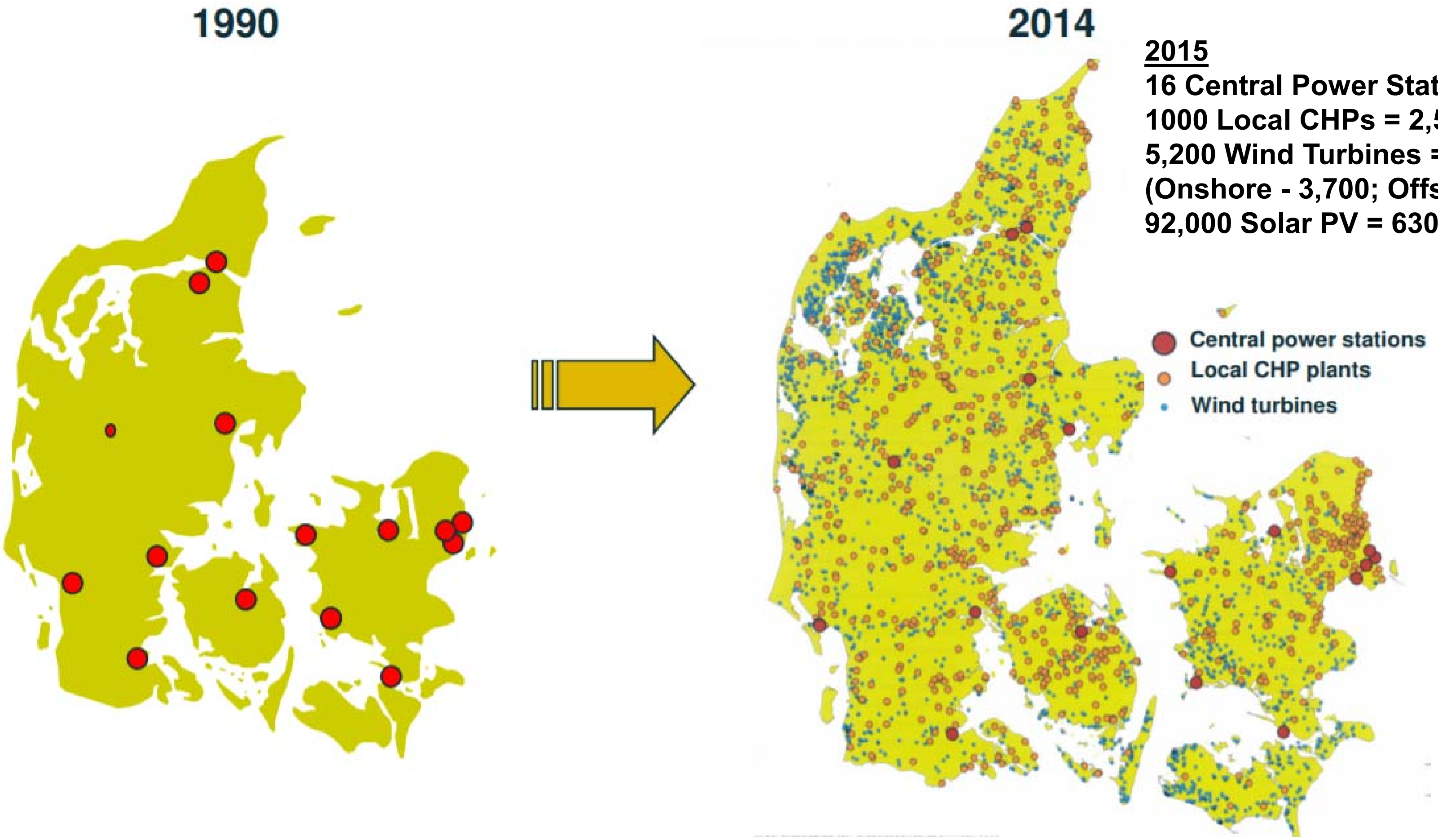
Wind farm operation

- WFC control
- Modelling of possible power modelling
- Short-term prediction

Planning and development of wind farms

- Wind farm projects and planning
- Environmental impact and planning - cold climates
- Social/public acceptance

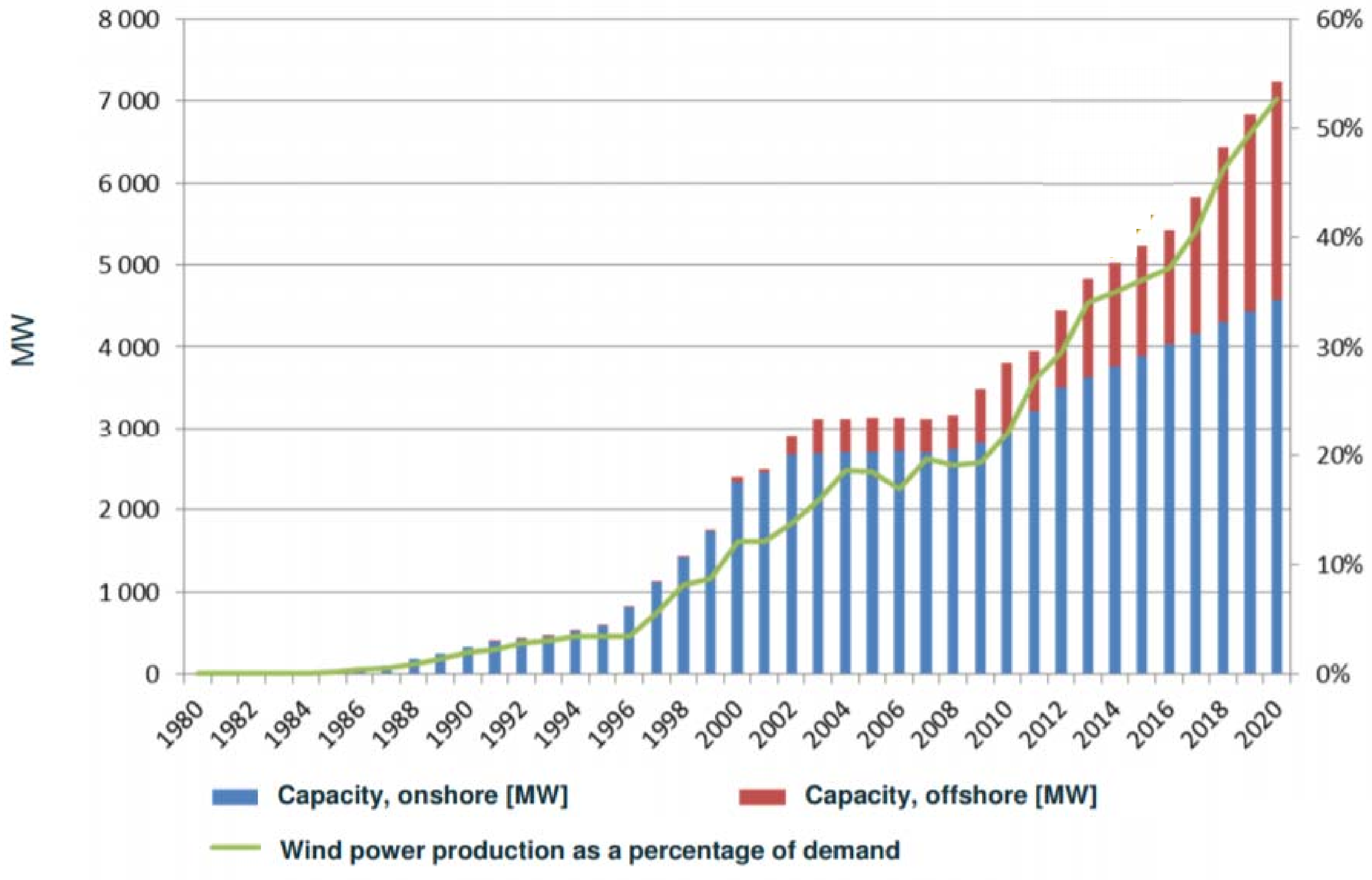
Centralized Plants Vs Distributed Generations



<u>2015</u>
16 Central Power Stations = 4,100 MW
1000 Local CHPs = 2,500 MW
5,200 Wind Turbines = 5,000 MW
(Onshore - 3,700; Offshore – 1,300 MW)
92,000 Solar PV = 630 MW

- Henning Parbo, “Distributed Generation Trends and Regulation: The Danish Experience”, EPRG Workshop on Distributed Generation and Smart Connections
- Henrik Klinge Jacobsen Stephanie Ropenus , “A Snapshot of the Danish Energy Transition in the Power Sector – An Overview”, Berlin 2015

Wind Power in Denmark



- Henning Parbo, “Distributed Generation Trends and Regulation: The Danish Experience”, EPRG Workshop on Distributed Generation and Smart Connections

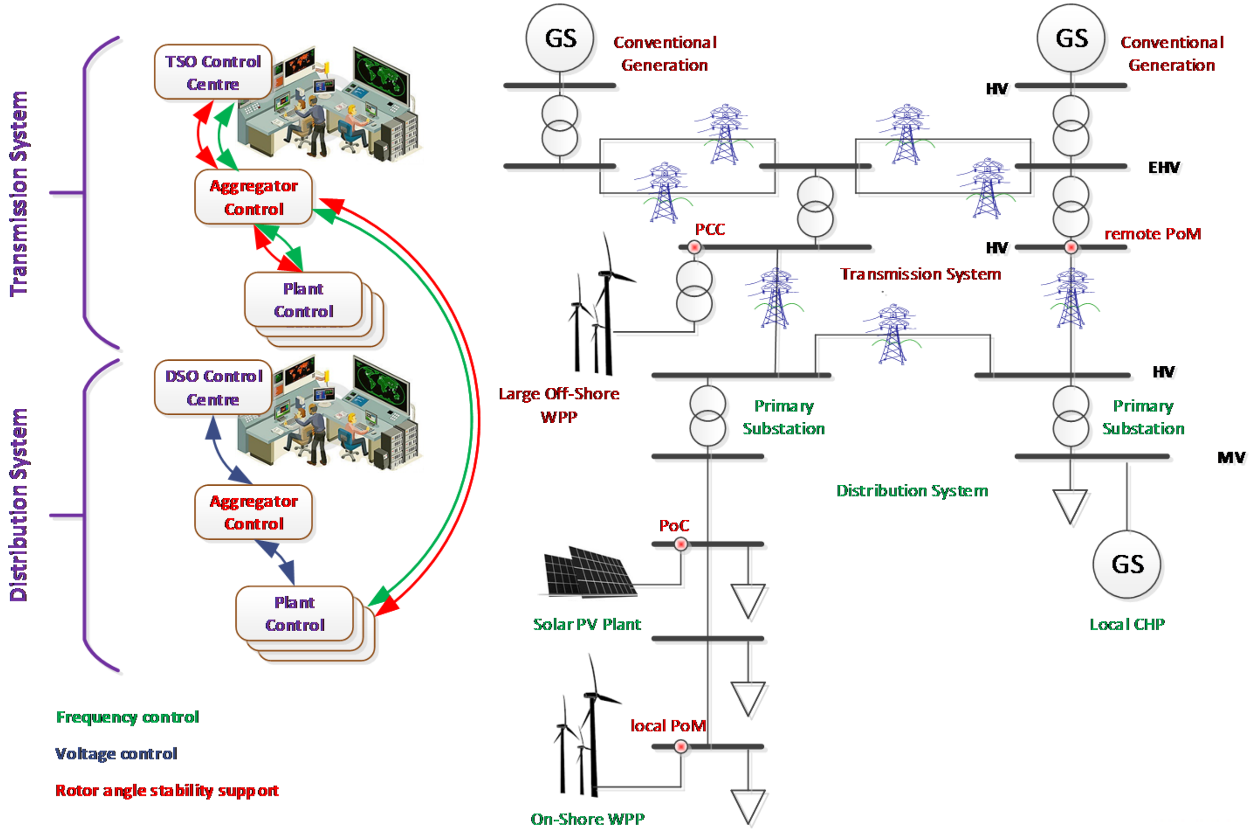
RePlan- Ancillary Services from Renewable Power Plants

Objective

To enable a resilient power system by developing technical solutions for the provision of ancillary services by renewable power plants

Partners:

DTU Wind Energy (leader)
DTU Elektro
AAU ET
AAU Wireless Communication Networks
Vestas Technology R&D



Project period:

1.03.2015 - 28.02.2018

Ongoing

More details at http://www.replanproject.dk/

RePlan- Ancillary Services from Renewable Power Plants

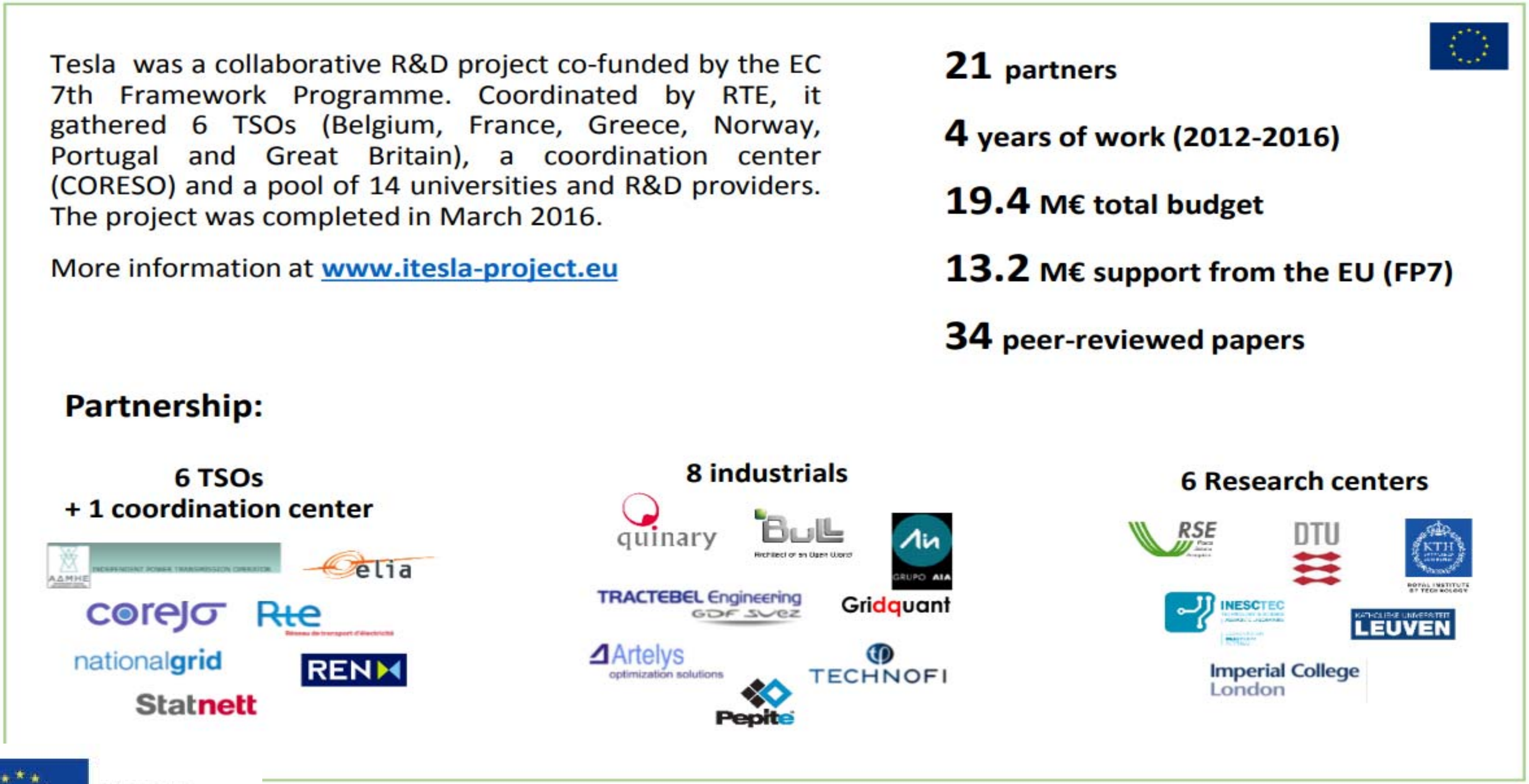
- develops controllers for the delivery of ancillary services from WP and PV plants , incorporating **communication** properties
- the services with great concern in the future include **voltage**, **frequency** and **rotor angular stability support**.
- uses state-of-the-art methods for simulation of renewable generation patterns and wind power forecast methods
- suitability **to coordinate** the provision of the services from WP and PV plants, identifying and analyzing their strengths and limitations
- impact of **communication** and **power availability forecast error** in providing coordination and ancillary services
- investigates and verifies ancillary services provision from WP and PV plants in **laboratory facilities** (large or real small power systems)

Deliverables and publications at http://www.replanproject.dk/

iTesla - Innovative Tools for Electrical System Security within Large Areas

Objectives

- To develop a toolbox that will be needed by TSOs to operate European power system in the years to come
- To validate this toolbox at the national and at the pan-European level



Tesla was a collaborative R&D project co-funded by the EC 7th Framework Programme. Coordinated by RTE, it gathered 6 TSOs (Belgium, France, Greece, Norway, Portugal and Great Britain), a coordination center (CORESO) and a pool of 14 universities and R&D providers. The project was completed in March 2016.

More information at www.itesla-project.eu

21 partners

4 years of work (2012-2016)

19.4 M€ total budget

13.2 M€ support from the EU (FP7)

34 peer-reviewed papers

Partnership:

6 TSOs
+ 1 coordination center

8 industrials

6 Research centers

iTesla - Innovative Tools for Electrical System Security within Large Areas

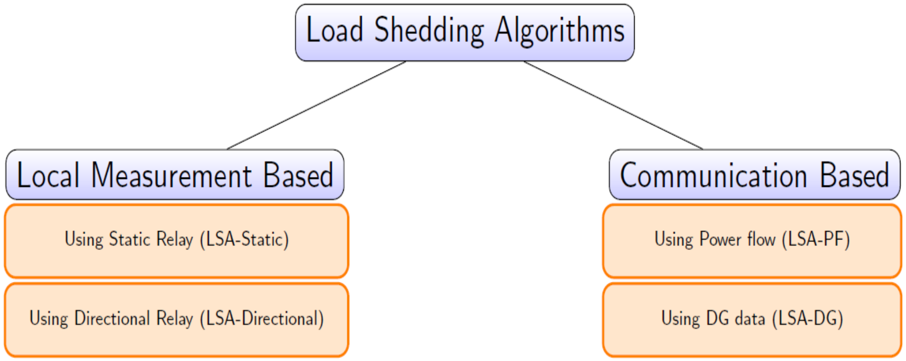
WP6: To review and assess the potential for more robust defence and restoration plan (led by DTU)

Improved Underfrequency Load Shedding (UFLS) Scheme Considering Distributed Generation

Impacts of high penetration of distributed generation on UFLS:

- Unintentional disconnection of DG
- Not disconnecting required amount of load
- Poor frequency response

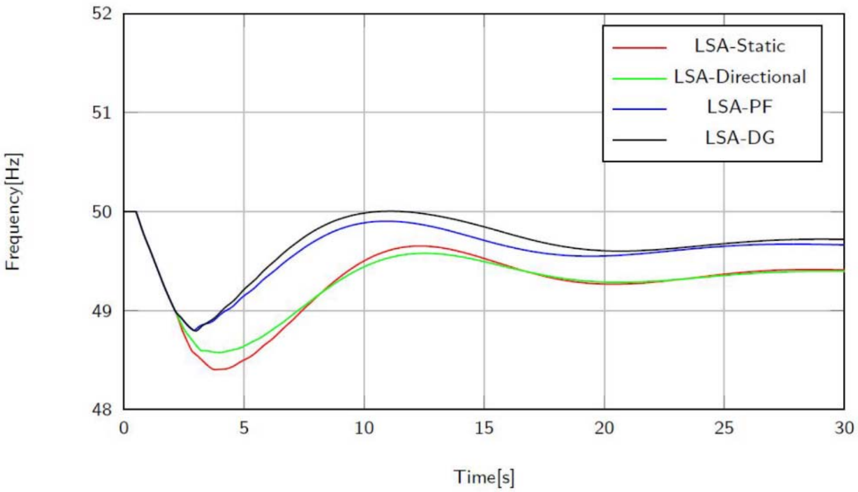
“IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration” - tripping feeders that have active DG certainly diminishes the beneficial affect of load shedding, and can even have negative impact by eliminating sources of generation that supports system inertia.



Load Shedding Algorithms

Local Measurement Based
- Using Static Relay (LSA-Static)
- Using Directional Relay (LSA-Directional)

Communication Based
- Using Power flow (LSA-PF)
- Using DG data (LSA-DG)



Kaushik Das, A Nitsas, M Altin, A Hansen, P Sørensen, “Improved Load Shedding Scheme considering Distributed Generation”, IEEE Transactions on Power Delivery, 2016

NetVind

Objectives

- Achieve **effective integration** of renewable energy in the MV grid
  - Minimizing unnecessary losses due to the new production
  - Use already installed power electronics in the wind turbine.
- The aim of the project is to exploit the connected wind turbines regulation capabilities **to obtain optimal operation** of the grid while the overall grid stabillity is taken into consideration.

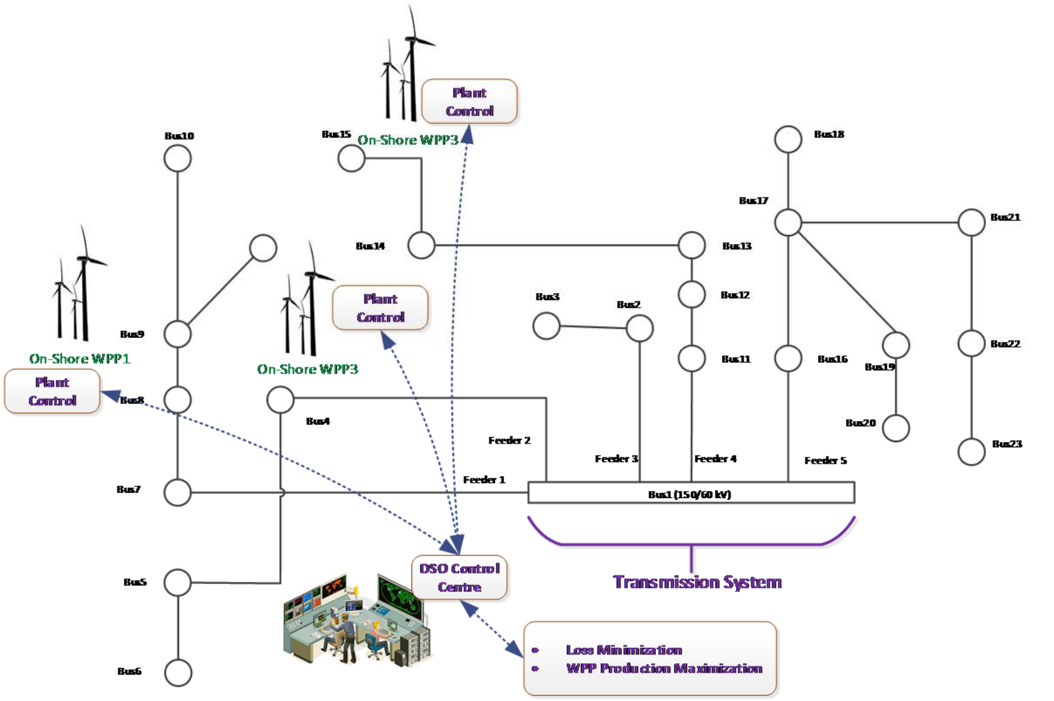
Partners:

ENIIG Forsyning A/S (leader)
DTU Wind Energy
Danish Energy Association

Project period:

Sep, 2016 – Sep, 2018

Ongoing



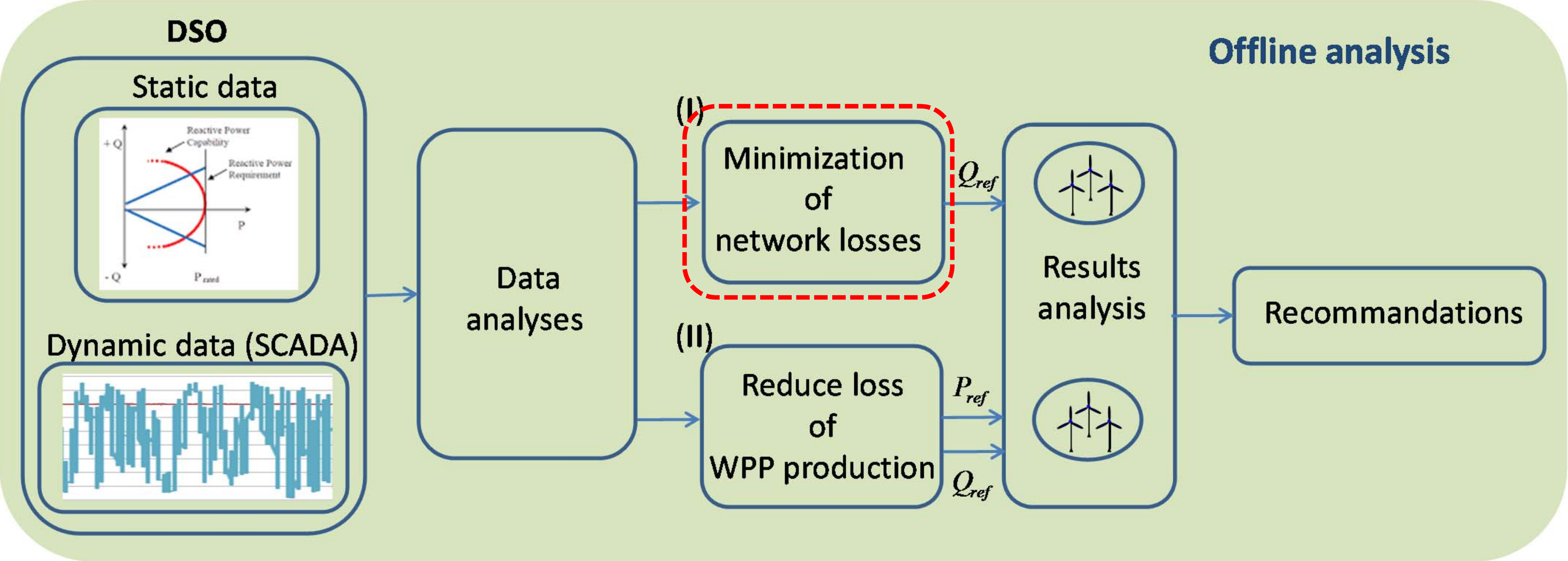
The project is supported by ForskEL

Actions planned – DSO point of view

- Exploit the existing grid optimally and secure the green transition in a socio-economical way, so we regulate instead of reinforce.
- Optimizing the grid loss for the DSO and secure compliance of demands in exchanging reactive power with the TSO in the 150/60 kV interface
- Digitize the communication between the wind turbines (WTs) and the DSO-SCADA system according to IEC 61850.
- Investigate the business model, which can be introduced to the business partners.
- Test and demonstrate the ICT-security infrastructure according to IEC 62351
- Test and demonstrate the algorithm and business model in a live laboratorium
- Gain knowhow for the future modelling of the MV-grid
- Qualifying the quality in future technical regulations which is developed by Danish TSO - Energinet

NetVind – offline analysis

- Analyze additional network losses due to wind power generation
- Develop methodologies for optimal control of Wind Power Plants (WPP):
  - to reduce network losses by optimizing the reactive power flow in 60kV network
  - to reduce the loss of power production from WPPs during network reconfigurations *(i.e. disconnections due to the repair and maintenance of the network)*



DSO

Static data

Dynamic data (SCADA)

Data analyses

(I)

Minimization of network losses

Q_{ref}

(II)

Reduce loss of WPP production

P_{ref}

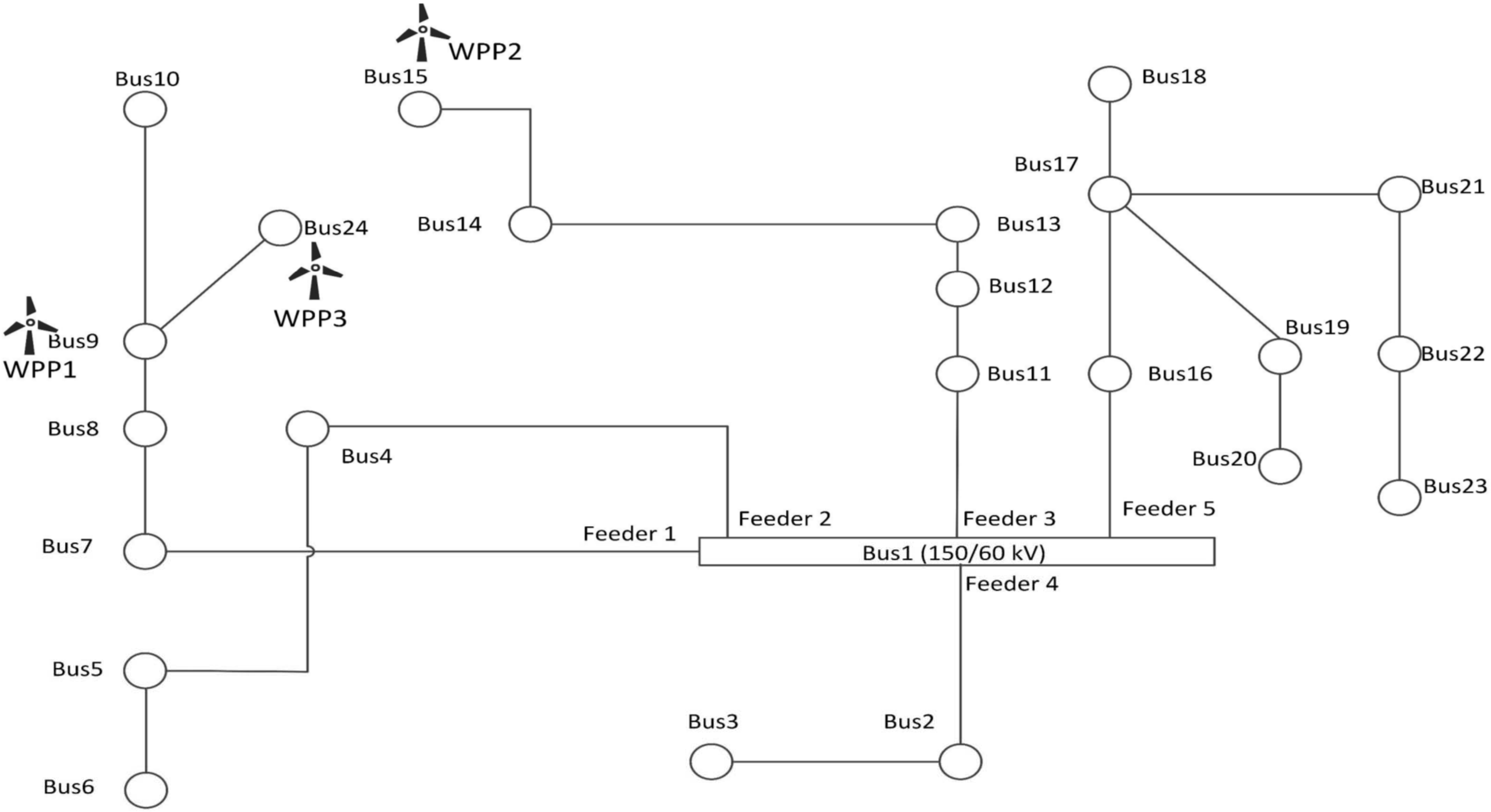
Q_{ref}

Results analysis

Recommandations

Offline analysis

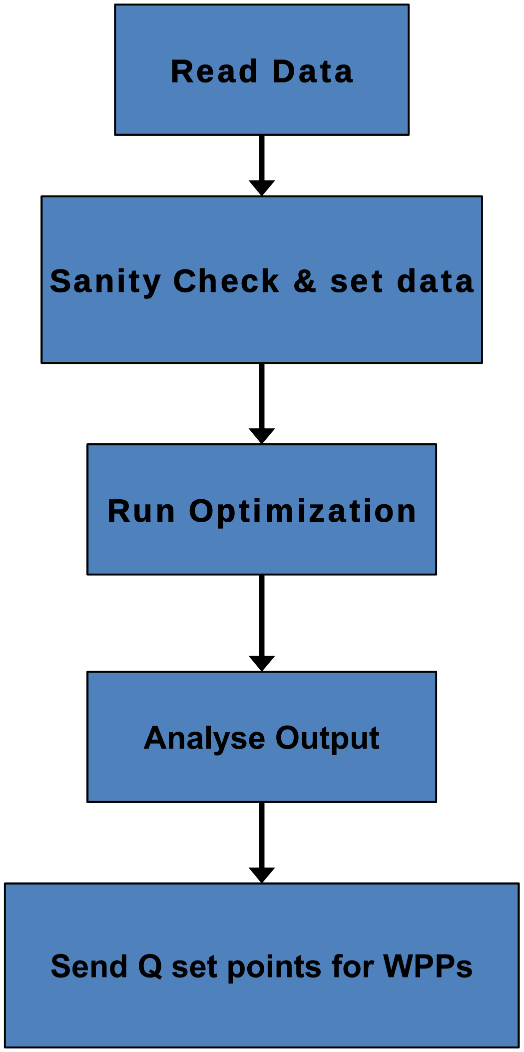
Topology


WPP2
Bus15
Bus10
Bus18
Bus17
Bus21
Bus24
Bus14
Bus13
WPP3
Bus12
Bus9
WPP1
Bus19
Bus22
Bus11
Bus16
Bus8
Bus4
Bus20
Bus23
Feeder 2
Feeder 3
Feeder 5
Feeder 1
Bus7
Bus1 (150/60 kV)
Feeder 4
Bus5
Bus3
Bus2
Bus6

Project Assumptions/ Considerations/ Constraints for offline analysis

- Topology assumed unchanged for the whole period of study
- Only control variables are Q set points of WPP
- 60/10 kV tap changers are not controlled by the optimization
- Using only healthy data from the complete data set
- Measurement accuracy not considered in this study
- Phases are balanced
- **Losses in WPP collection grid not considered**

Flowchart – Minimization of network losses



Read Data

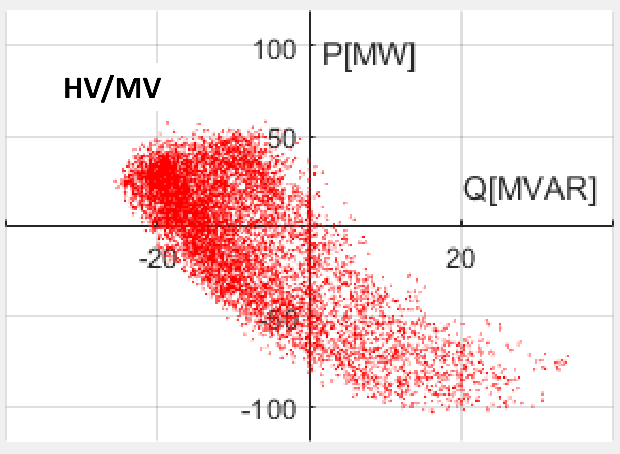
Sanity Check & set data

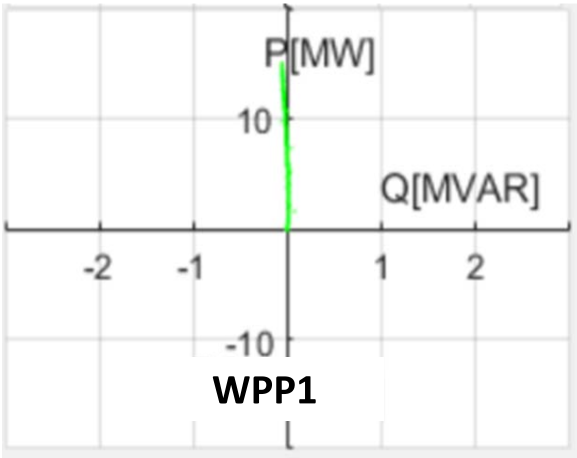
Run Optimization

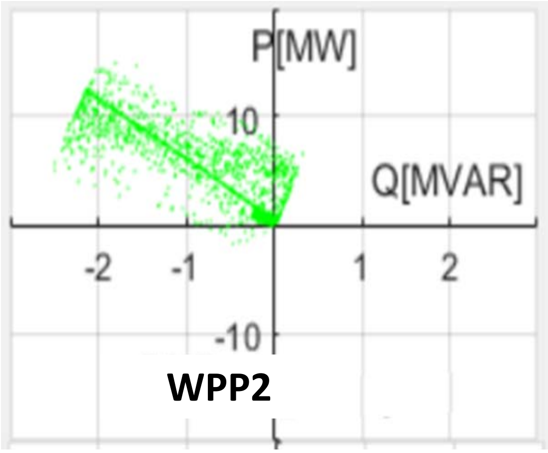
Analyse Output

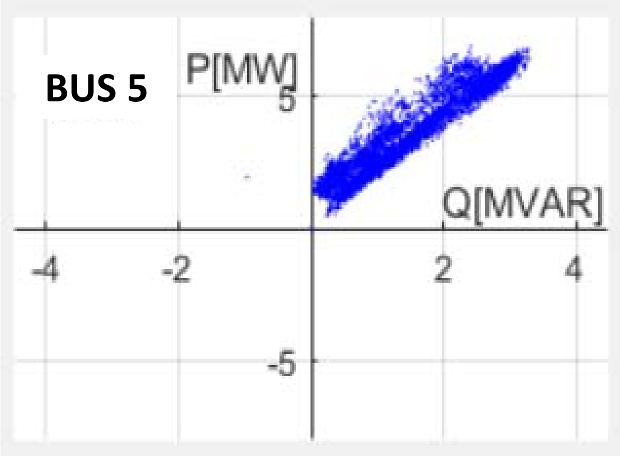
Send Q set points for WPPs

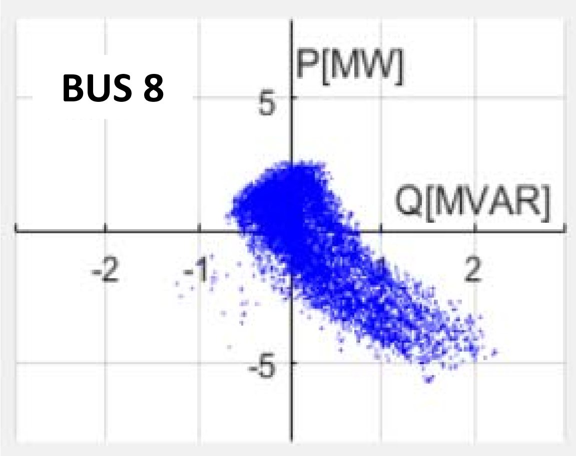
Network Characteristics

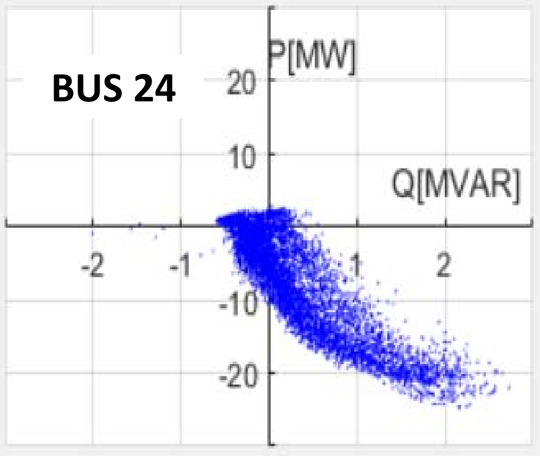




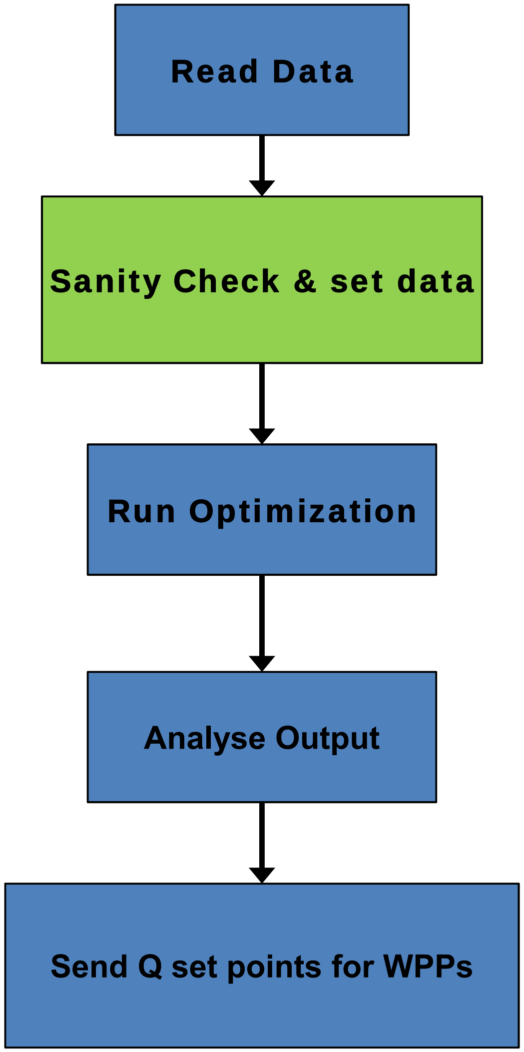






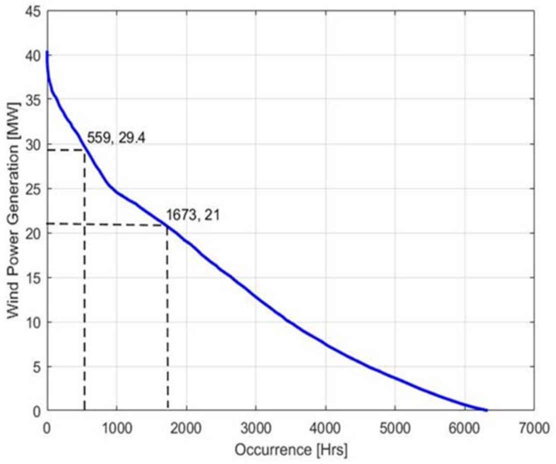


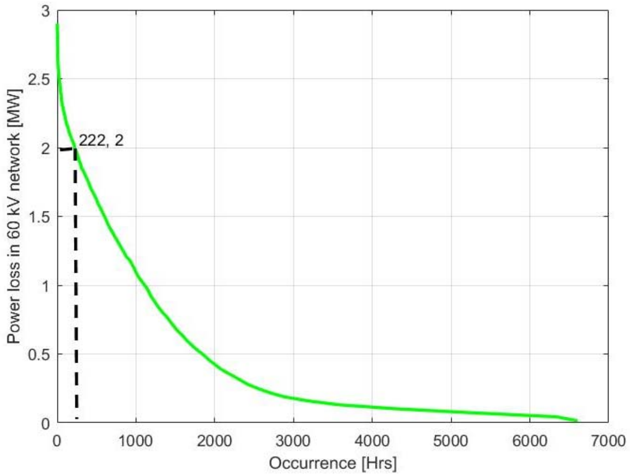
Sanity Check & set data

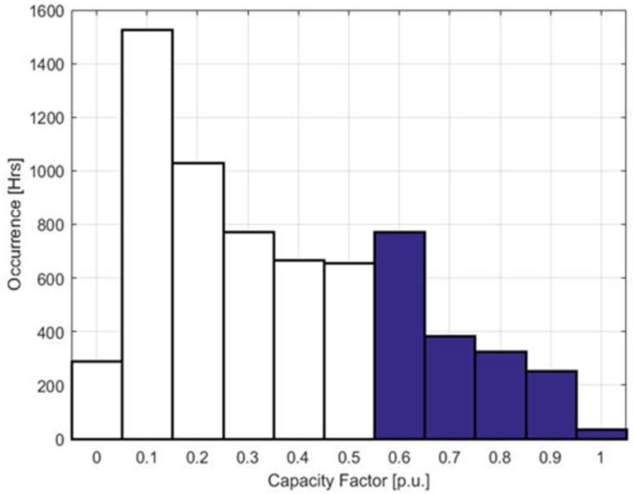


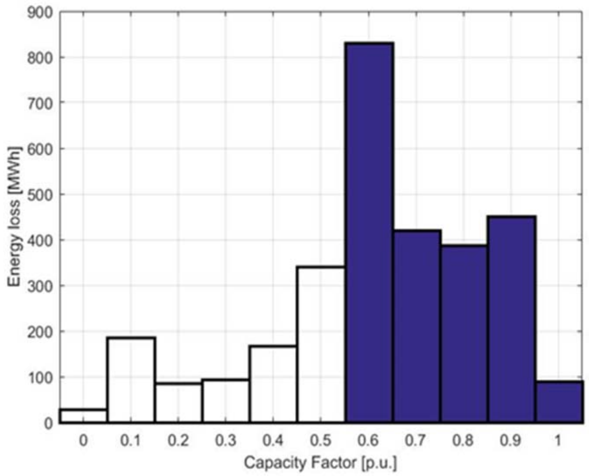
- Check if all required data (load and generation) are available
- Check if there is any overloading in the lines/transformers, then discard that data point
- State Estimation can be performed in future for more accurate filtering
  - State estimation may also require automated meter-reading (AMR) data

Input Data Analysis


Duration curve for Wind Power Generation


Duration curve for power loss in 60 kV network

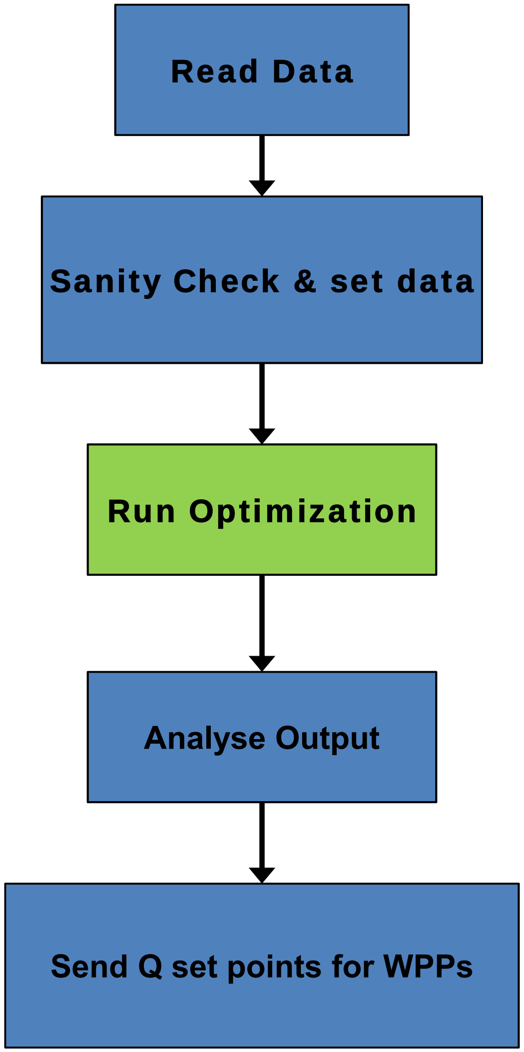

Operational hours for WPPs at different capacity factors


Energy loss in the 60 kV network for different WPP capacity factors

Higher is wind power generation, higher is network loss

Although high wind power generation occurs for small duration, it contributes for major proportion of energy loss

Optimization



Read Data

Sanity Check & set data

Run Optimization

Analyse Output

Send Q set points for WPPs

- Control variables:
  - Reactive power set point of 3 WPPs

- Objective:
  - Minimize active power loss in 60 kV feeders

- Constraints

  Network constraints

  - MVAR flow < 0.48 * Capacity in 150/60 kV transformer
  - Loading of 60 kV feeders < 100%
  - Loading of 60kV/10kV transformers < 100%

    (can be allowed up to 120% for small amount time)

  - 59kV < Voltage at 60 kV busbars < 66kV

  WPP constraint

  - Q lower capability< Q set points < Q upper capability

Optimization

Read Data

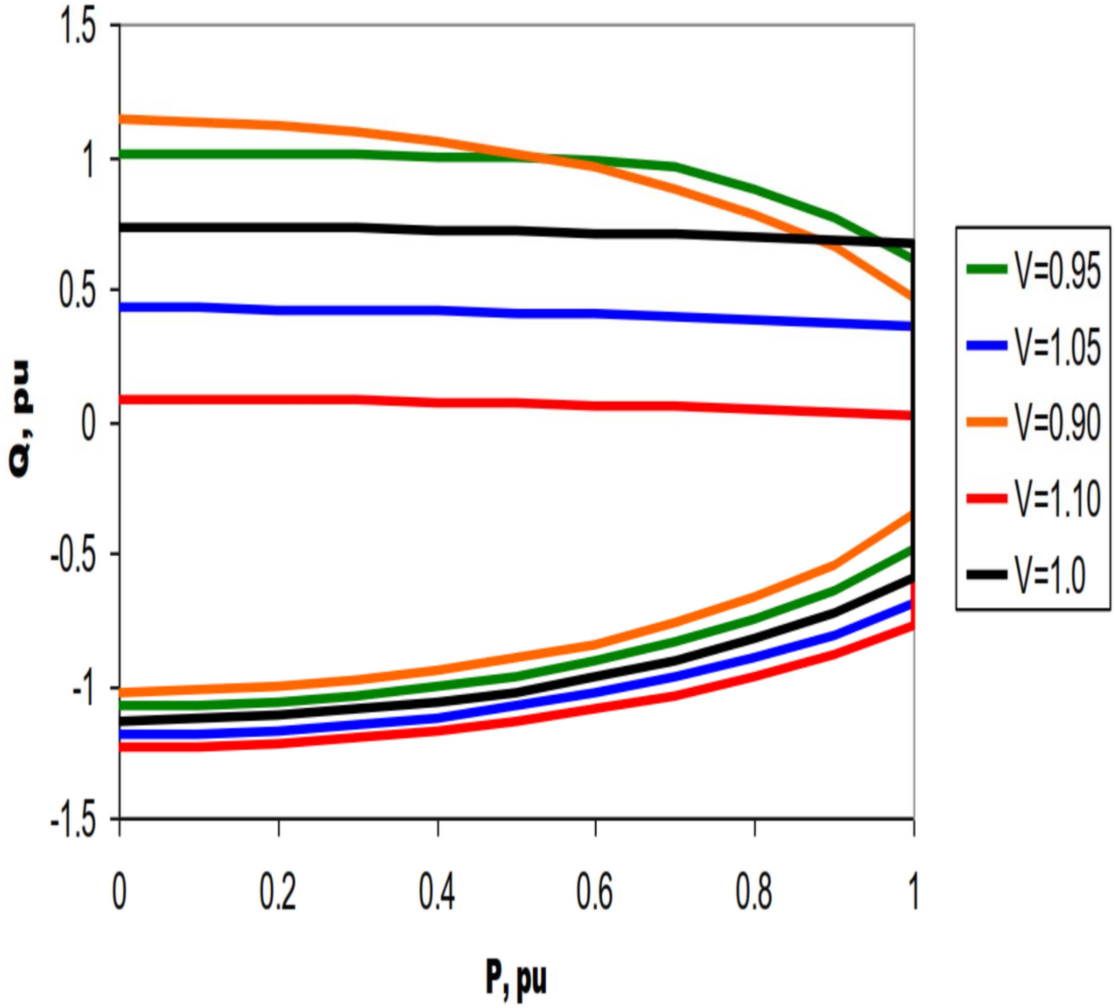
Sanity Check & set data

Run Optimization

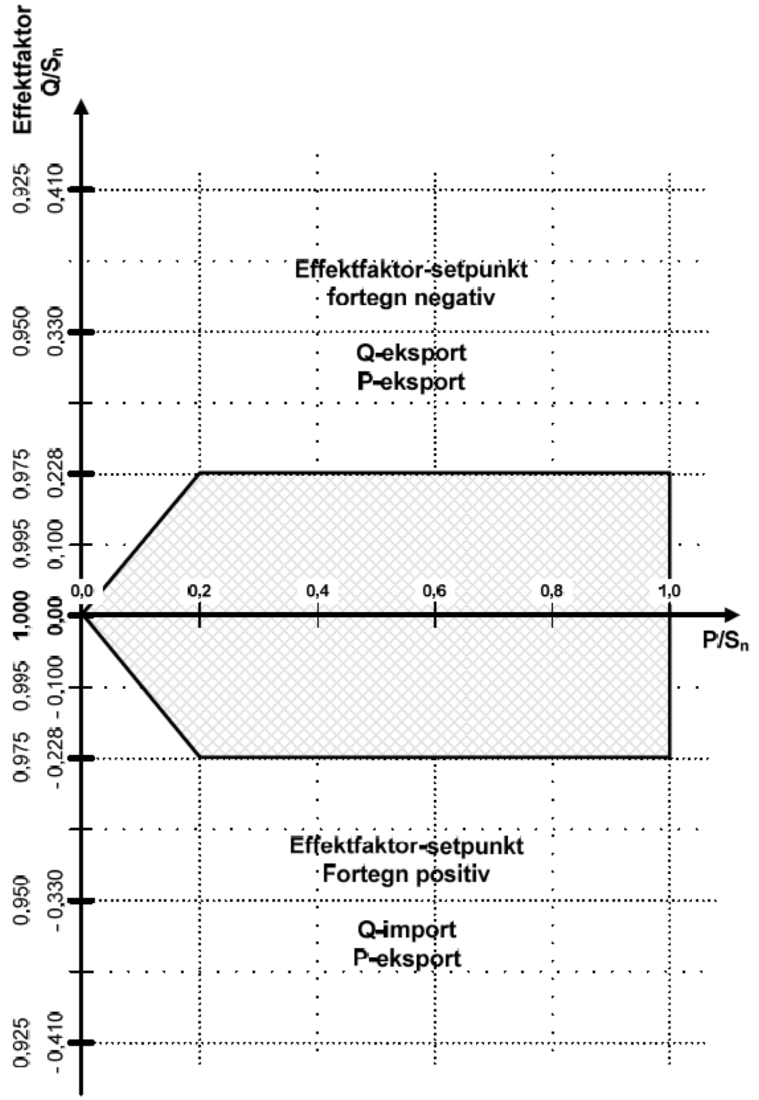
Analyse Output

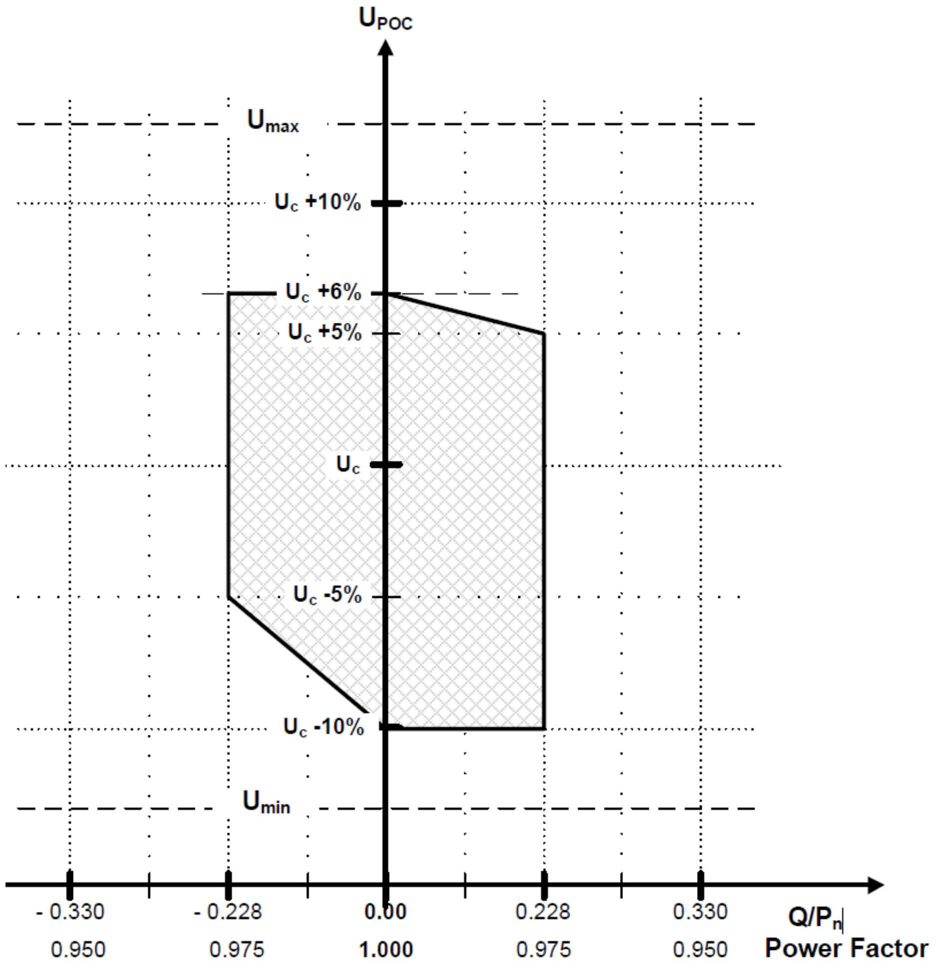
Send Q setpoints for WPPs

Q lower capability< Q set points < Q upper capability



Optimization





Optimization: Method

	Meta-heuristic Optimization	**Mathematical Optimization**
Handle non-linearities	✓	✗
Jacobian/Sensitivity matrix is not required	✓	✗
Global optimum	✓	✗
Less complex mathematical formulation/ less prone to human error	✓	✗
Easy to add new objectives / constraints	✓	✗
Easily adaptable for other distribution system topologies	✓	✗
Efficient in handling both continuous and discrete variables	✓	✗
Less sensitive to optimization parameters	✗	✓
Less Computation Time	✗	✓
Better understanding and knowhow	✗	✓
Less implementation Complexity	✗	✓

Mathematical Optimization : Interior Point Method

Meta-heuristic Optimization : Genetic Algorithm, Particle Swarm Method

Particle Swarm Optimization (PSO)

Why PSO?

- Particularly **resistant in local optimum entrapment**
- Can handle both **discrete** and **continuous decision variables**
- **Outperforms** most intelligent search methods both in terms of **computational effort** needed and **results generated**

Basic Elements of PSO

- **Particle:** An agent that contains the values of the decision variables and is used to search the solution space
- **Swarm:** A group of particles
- **Fitness Function:** A function used to evaluate the fitness of each particle at each iteration

Mathematical Formulation of Particle Swarm Optimization (PSO)

$$\overbrace{\boldsymbol{x_i} = [x_{i1}, x_{i2}, ..., x_{id}, ..., x_{in}]^T}^{\textbf{Particle i}}$$

$$\underbrace{\boldsymbol{u_i} = [u_{i1}, u_{i2}, ..., u_{id}, ..., u_{in}]^T}_{\text{Velocity of particle i}}$$

$$\overbrace{\boldsymbol{p_i} = [p_{i1}, p_{i2}, ..., p_{id}, ..., p_{in}]^T}^{\textbf{Personal best of particle i}}$$

$$\underbrace{\boldsymbol{g} = [g_1, g_2, ..., g_d, ..., g_n]^T}_{\text{Collective best of the swarm}}$$

$$\overbrace{u_{id}(t+1) = w(t) \cdot u_{id}(t) + c_1(t) \cdot r_1 \cdot (p_{id}(t) - x_{id}(t)) + c_2(t) \cdot r_2 \cdot (g_d(t) - x_{id}(t))}^{\text{Velocity update equation}}$$

$$\underbrace{x_{id}(t+1) = x_{id}(t) + u_{id}(t+1)}_{\text{Position update equation}}$$

$w(t)$ is the **inertia weight factor**

r_1 , $r_2 \in [0, 1]$ and are randomly produced at each iteration

c_1 , c_2 are the **cognitive** and **social** coefficients respectively

Linearly Decreasing Inertia Weight PSO (LDW-PSO)

$$w(t) = w_{max} - \frac{w_{max} - w_{min}}{t_{max}} \cdot t$$

$$c_1 = \text{constant}$$

$$c_2 = \text{constant}$$

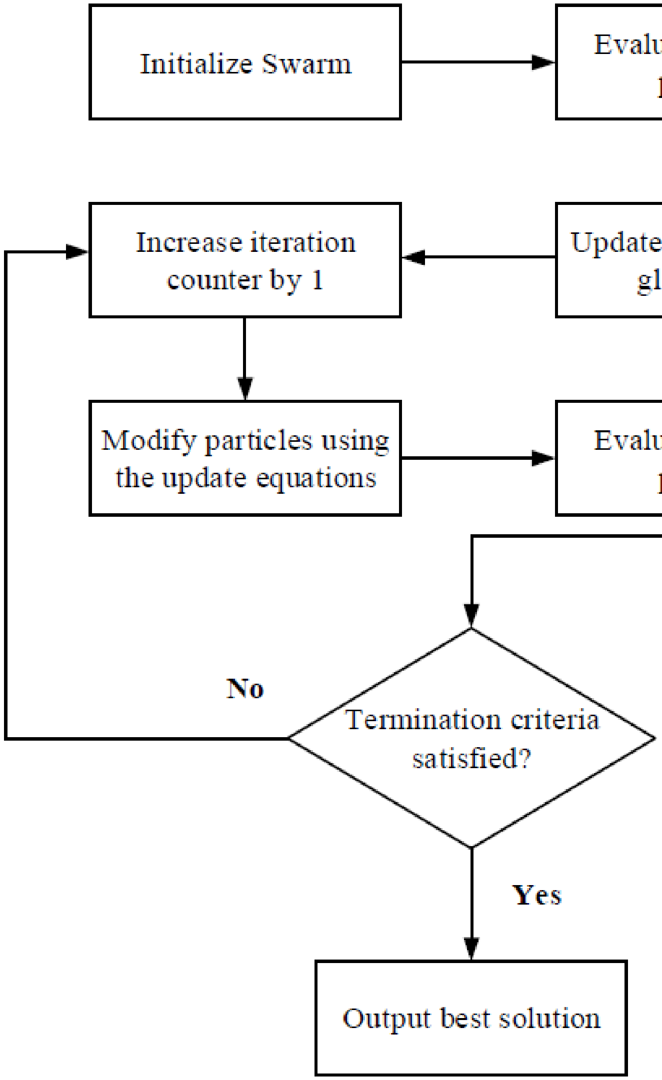
Time Varying Acceleration Coefficients PSO (TVAC-PSO)

$$w(t) = w_{max} - \frac{w_{max} - w_{min}}{t_{max}} \cdot t$$

$$c_1(t) = c_1^{max} + \frac{c_1^{min} - c_1^{max}}{t_{max}} \cdot t$$

$$c_2(t) = c_2^{min} + \frac{c_2^{max} - c_2^{min}}{t_{max}} \cdot t$$

Flowchart of LDW-PSO and TVAC-PSO



Multi-objective Optimization (using PSO)

Objective1 : Loss Minimization

Objective2 : Minimization of MVAR flow between MV and HV network

WT Capability

Swarm Size = 30 , Initial P_{loss} (kW) = 3135.74 , Initial Q_{tr} (kVar) =-26011.16

	Simulation Number	Q_1 (MVar)	Q_2 (MVar)	Q_3 (MVar)	ΔP_{loss} %	ΔQ_{tr} %	ΔF %
LDW-PSO	3	5.098	4.760	7.453	-7.23	-71.42	-32.83
	7	7.417	8.272	7.586	-5.65	-94.93	-43.17
	8	7.400	8.808	5.777	-4.82	-89.5	-40.09
	9	5.391	7.759	8.064	-6.72	-86.95	-40.69
TVAC-PSO	2	4.349	9.211	8.009	-6.68	-88.35	-41.25
	3	6.928	7.852	6.839	-5.81	-88.31	-40.73
	7	7.113	7.721	7.494	-5.96	-91.21	-41.56
	8	4.347	7.775	5.518	-6.17	-72.41	-34.23

Highest reduction of power losses but low reduction of reactive power import

Increasing Q of the WPPs does not necessarily mean that the losses will further decrease

Grid Code Requirements

Initial P_{loss} (kW) = 3135.74 , Initial Q_{tr} (kVar) = -26011.16

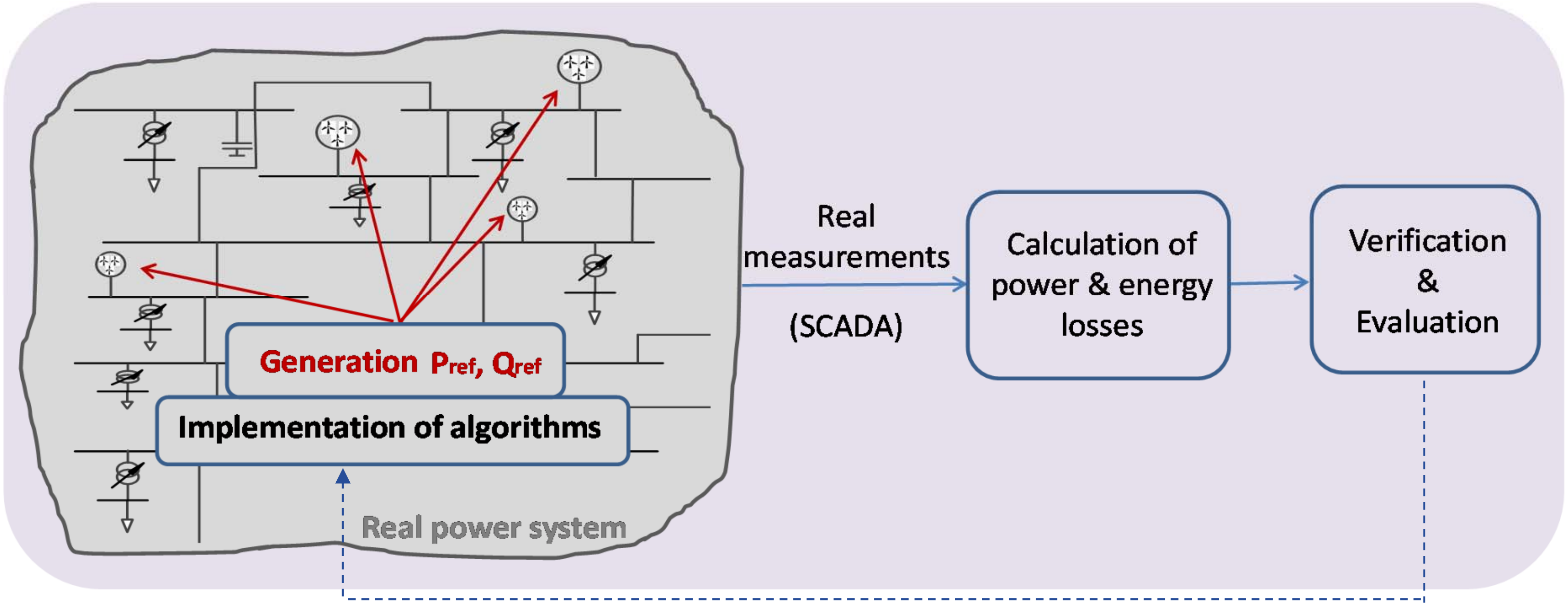
Algorithm	Simulations Executed	Swarm Size	Q1 MVar	Q2 MVar	Q3 MVar	ΔP_{loss} %	ΔQ_{tr} %
LDW-PSO	10	10	2.736	3.420	2.736	-4.65	-36.88
	10	30	2.736	3.420	2.736	-4.65	-36.88
TVAC-PSO	10	10	2.736	3.420	2.736	-4.65	-36.88
	10	30	2.736	3.420	2.736	-4.65	-36.88

Time series Analysis

Without Optimization			**With Optimization**		
			Loss reduction [%]		Energy Saving [MWh]
Power loss [MW]	Number of Hrs	Energy loss [MWh]	Mean	Uncertainty	
0-500	6321	949	3.86%	0.25%	36.6 ± 2.38
500-1000	967	695	0.89%	0.10%	6.2 ± 0.69
1000-1500	674	833	1.84%	0.11%	15.33 ± 0.92
>1500	798	1539	2.91%	0.08%	44.78 ± 1.23
Sum	8760	4016			**103 ± 2.92**

Using optimization method, estimated energy saving is 103 ± 2.92 MWh

Online operation and validation



Real measurements (SCADA)

Calculation of power & energy losses

Verification & Evaluation

- Set up is being done, real-time validation expected to be started in September

- Validation:
  - Communication capabilities
  - Different optimization methods
  - Frequency of optimization – 15 mins / 30 mins / 1 hour
  - Energy savings over a year
  - Grid code requirements vs WT capability

Conclusion

NetVind (Phase 1) – Ongoing research work

- Energy savings is possible through optimal control of wind power plants
- Without additional investment on equipment like synchronous condensers.
- WPPs have higher capability to support network than the grid code requirements.

Real time validation to be started in September

Phase 2

Q control

- Using wind power support for optimization of distribution network operation:
  - Control of MVAR infeed to the transmission network
  - Voltage control in 60/10 kV network
  - Loss minimization
    - Both in the distribution network and WPP collection system
- Control WPP tap changers and load tap changers together with wind power for optimization
- Dynamic studies for improvement of voltage stability using co-ordinated voltage control of WPPs, tap-changers etc.

P control

- Algorithm to reduce lost wind power production during maintenance
- Optimal feeder disconnection for load reduction/shedding without disconnecting renewable sources (mainly PV)

Monitoring

- Improved filtering of input SCADA data and consider measurement inaccuracies in optimisation

Thank you for your attention.