INNOVATIVE TOOLS FOR OFFSHORE WIND AND DC GRIDS

Enhancement to SCADA/EMS for hybrid AC/DC networks

Motaz Ayiad – ESR14

Supervisors:

FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Prof. Helder Leite

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Marie Sklodowska-Curie funding
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State Estimation for Hybrid VSC Based HVDC/AC Transmission Networks

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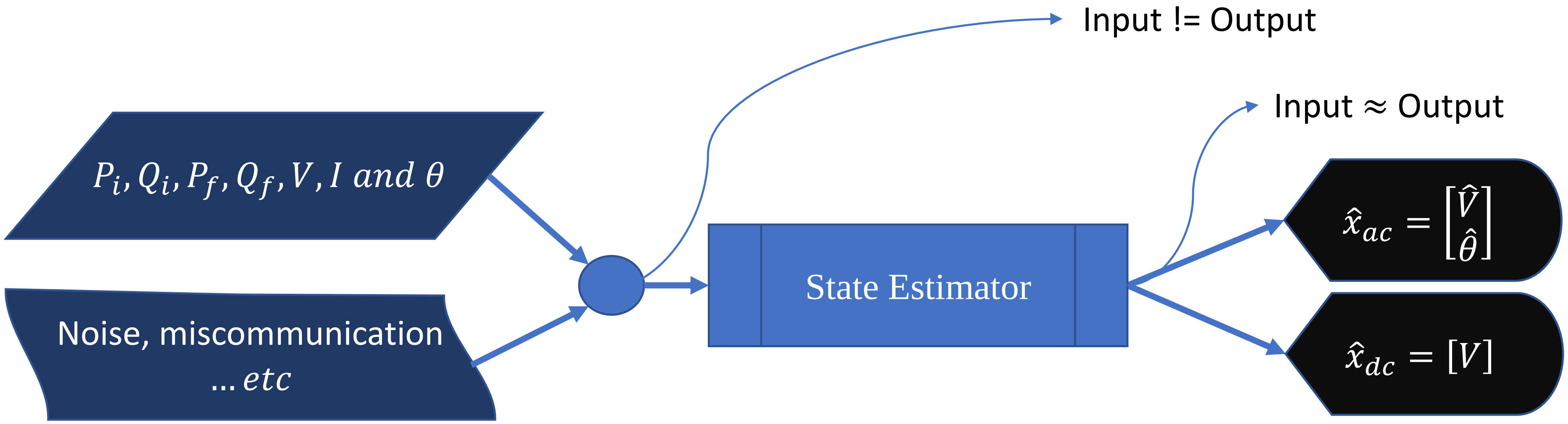
1 slide revision

State Estimation



$$z = h(x) + \varepsilon$$

ε – error

$h(x)$ - measurement function (pf,inj…)

z– measurements

Aim: minmize(ε)

$$WLS_{obj}(x) = \sum_{i=1}^{n} \frac{r_i^2}{\sigma_i{}^2} = \sum_{i=1}^{n} \frac{\left(z_i - h_i(x)\right)^2}{R_{ii}{}^2}$$

The Unified Hybrid State Estimation

Unified State Estimation

Extending the WLS AC state estimation to include the DC side and converter components:

Decentralized

1- Measurement vector (z):

$z = [zAC_1 zAC_2 \ \dots zAC_n \mid zDC_1 zDC_2 \ \dots zDC_m|$

Voltage Coupling

$zConv_1 zConv_2 \ \dots zConv_k|$

Power Coupling

$z_{factor_1} z_{factor_2} \dots z_{factor_k}];$

2- Measurement function vector (h(x)):

$$h(x) = [hAC_1 hAC_2 \ \dots hAC_n \mid hDC_1 hDC_2 \ \dots hDC_m \mid hConv_1 hConv_2 \ \dots hConv_k | h_{factor_1} h_{factor_2} \dots h_{factor_k}];$$

Power Coupling

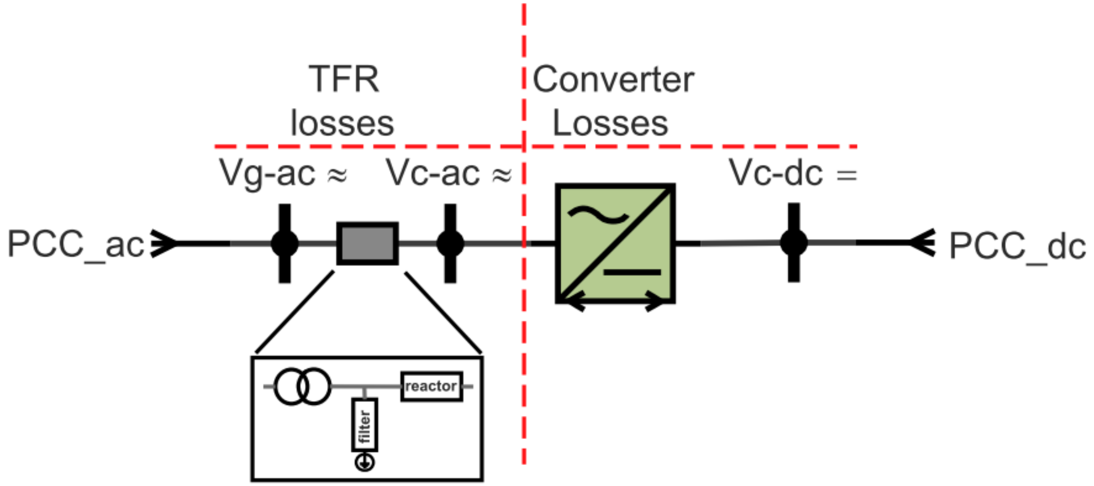
$hConv(x) = P_{ac} + P_{dc} + P_{convloss} = 0$ is a power constraint, where:

- $P_{convloss} = a + b \times I_c + c \times {I_c}^2$ [1,2];

- a: the transformers and averaged axillary equipment no load losses;
- b: the freewheeling diodes and switching losses;
- c: the conduction losses;
- I_c: the current flow through the converter.

Transformer, Filter and Reactor (TFR) losses are considered in the AC side.

Impact: improves measurements estimations.



[1] - HVDC Grid Layouts: For Offshore and Supergrid of the Future
[2] - Optimal Power Flow for AC/DC Grids: Formulation, Convex Relaxation, Linear Approximation, and Implementation

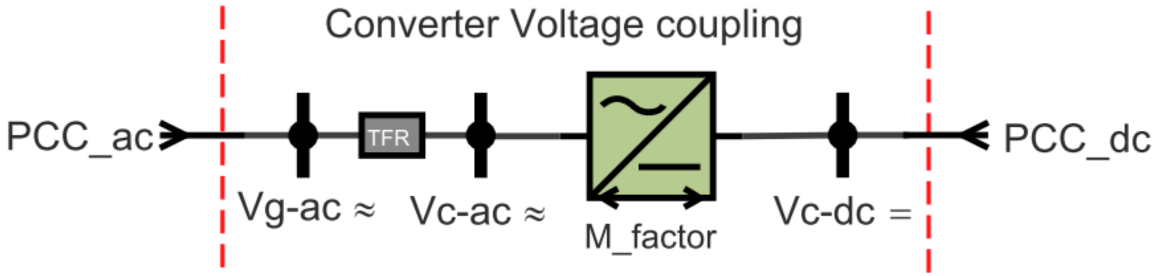
Voltage Coupling Factor - M_{factor}

$h_{factor} = M_{factor} = K\,\frac{V_{c-dc}}{V_{g-ac}}$ is the converter voltage coupling index, it can be rearranged as a constraint:
$M_{factor} \times V_{g-ac} - \mathrm{K} \times V_{c-dc} = 0$ where:

- $V_{g-ac} = \begin{cases} V_{c-ac} + V_{TFR}, & \text{for rectifier} \\ V_{c-ac} - V_{TFR}, & \text{for inverter} \end{cases}$

- K: the voltage conversion factor, it can have different values based on the AC side network topology and converter type (details in [3])

Impact: improves system states estimations.



[3] - VSC-FACTS-HVDC: Analysis, Modelling and Simulation in Power Grids

Unified WLS Jacobian Matrix

The Current Jacobian solution:

$$H_{unified}(x) = \begin{bmatrix} H_{(AC-AC)_1} & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & H_{(AC-AC)_2} & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & H_{(AC-AC)_n} & \dots & 0 & 0 & 0 \\ 0 & 0 & 0 & \dots & H_{(DC-DC)_1} & 0 & 0 \\ 0 & 0 & 0 & \dots & 0 & H_{(DC-DC)_2} & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & H_{(DC-DC)_m} \\ H_{(Conv-AC)_1} & 0 & 0 & \dots & H_{(Conv-DC)_1} & 0 & 0 \\ 0 & H_{(Conv-AC)_2} & 0 & \dots & 0 & H_{(Conv-DC)_2} & 0 \\ 0 & 0 & H_{(Conv-AC)_k} & \dots & 0 & 0 & H_{(Conv-DC)_k} \\ H_{(M-AC)_1} & 0 & 0 & \dots & H_{(M-DC)_1} & 0 & 0 \\ 0 & H_{(M-AC)_2} & 0 & \dots & 0 & H_{(M-DC)_2} & 0 \\ 0 & 0 & H_{(M-AC)_k} & \dots & 0 & 0 & H_{(M-DC)_k} \end{bmatrix}$$

$n\ is\ number\ of\ AC\ systems$

$m\ is\ number\ of\ DC\ systems$

$k\ is\ number\ of\ Converters$

Jacobian Matrix: AC and DC components

$$H_{AC-AC}(x) = \frac{\partial h_{ac-ac}(x)}{\partial x} = \begin{bmatrix} \frac{\partial h_0(x)}{\partial \theta} & \frac{\partial h_0(x)}{\partial V_{ac}} \\ \frac{\partial h_1(x)}{\partial \theta} & \frac{\partial h_1(x)}{\partial V_{ac}} \\ \frac{\partial h_2(x)}{\partial \theta} & \frac{\partial h_2(x)}{\partial V_{ac}} \\ \frac{\partial h_3(x)}{\partial \theta} & \frac{\partial h_3(x)}{\partial V_{ac}} \\ \frac{\partial h_4(x)}{\partial \theta} & \frac{\partial h_4(x)}{\partial V_{ac}} \\ \frac{\partial h_5(x)}{\partial \theta} & \frac{\partial h_5(x)}{\partial V_{ac}} \end{bmatrix}$$

Where:
$h_0(x)$ is Voltage measurements
$h_1(x)$ is Active power Injection measurements
$h_2(x)$ is Reactive power Injection measurements
$h_3(x)$ is Active power flow measurements
$h_4(x)$ is Reactive power flow measurements
$h_5(x)$ is Current flow measurements

$$H_{DC-DC}(x) = \frac{\partial h_{dc-dc}(x)}{\partial x} = \begin{bmatrix} \frac{\partial h_0(x)}{\partial V_{dc}} \\ \frac{\partial h_1(x)}{\partial V_{dc}} \\ \frac{\partial h_3(x)}{\partial V_{dc}} \\ \frac{\partial h_5(x)}{\partial V_{dc}} \end{bmatrix}$$

Where:
$h_0(x)$ is Voltage measurements
$h_1(x)$ is Real power Injection measurements
$h_3(x)$ is Real power flow measurements
$h_5(x)$ is Current flow measurements

Jacobian Matrix: P-coupling components

DC Side	AC Side
$H_{Conv-DC}(x) = \left[\frac{\partial h_1(x)}{\partial V_{dc}} \right] = \frac{\partial Pdc_{inj}}{\partial V_{dc}} = V_{dc}(\, pG_{m_{ij}})$	$H_{Conv-AC}(x) = \left[\frac{\partial h_1(x)}{\partial \theta} \quad \frac{\partial h_1(x)}{\partial V_{ac}} \right]$

Where:
$h_1(x)$ is Power coupling constraint

Jacobian Matrix: P-coupling components

AC Side

$$\frac{\partial h_1(x)}{\partial V_{ac}} = \frac{\partial Pac_{inj}}{\partial V_{ac}} + \frac{P_{convloss}}{\partial V_{ac}}$$

$$\frac{\partial h_1(x)}{\partial V_{ac}} = \frac{\partial Pac_{inj}}{\partial V_{ac}} + b\left(\frac{Pac_{inj}\frac{\partial Pac_{inj}}{\partial V_{ac}} + Qac_{inj}\frac{\partial Qac_{inj}}{\partial V_{ac}}}{Vac\sqrt{Pac_{inj}^2 + Qac_{inj}^2}} - \frac{\sqrt{Pac_{inj}^2 + Qac_{inj}^2}}{Vac^2}\frac{\partial V_{ac}}{\partial V_{ac}}\right)$$
$$+2c\left(\frac{Pac_{inj}\frac{\partial Pac_{inj}}{\partial V_{ac}} + Qac_{inj}\frac{\partial Qac_{inj}}{\partial V_{ac}}}{Vac^2} - \frac{(Pac_{inj}^2 + Qac_{inj}^2)}{Vac^3}\frac{\partial V_{ac}}{\partial V_{ac}}\right)$$

$$\frac{\partial h_1(x)}{\partial \theta} = \frac{\partial Pac_{inj}}{\partial \theta} + \frac{P_{convloss}}{\partial \theta}$$

$$\frac{\partial h_1(x)}{\partial \theta} = \frac{\partial Pac_{inj}}{\partial \theta} + b\left(\frac{Pac_{inj}\frac{\partial Pac_{inj}}{\partial \theta} + Qac_{inj}\frac{\partial Qac_{inj}}{\partial \theta}}{Vac\sqrt{Pac_{inj}^2 + Qac_{inj}^2}}\right) + 2c\left(\frac{Pac_{inj}\frac{\partial Pac_{inj}}{\partial \theta} + Qac_{inj}\frac{\partial Qac_{inj}}{\partial \theta}}{Vac^2}\right)$$

Jacobian Matrix: V-coupling components

DC Side	AC Side
$H_{M-DC}(x) = \left[\frac{\partial h_1(x)}{\partial V_{c-dc}} \right] = \frac{\partial V_{c-dc}}{\partial V_{c-dc}} \frac{K}{V_{g-ac}} = \frac{K}{V_{g-ac}}$	$H_{M-AC}(x) = \left[\frac{\partial h_1(x)}{\partial \theta} \quad \frac{\partial h_1(x)}{\partial V_{g-ac}} \right]$

Where:
$h_1(x)$ is Voltage coupling constraint

Jacobian Matrix: V-coupling components

AC Side

$$\frac{\partial h_1(x)}{\partial V_{g-ac}} = \frac{\partial V_{g-ac}}{\partial V_{g-ac}} \frac{-KV_{c-dc}}{V_{g-ac}^2} = \frac{-KV_{c-dc}}{V_{g-ac}^2}$$

$$\frac{\partial h_1(x)}{\partial \theta} = 0$$

Test Case: Cigre B4 DC grids test system

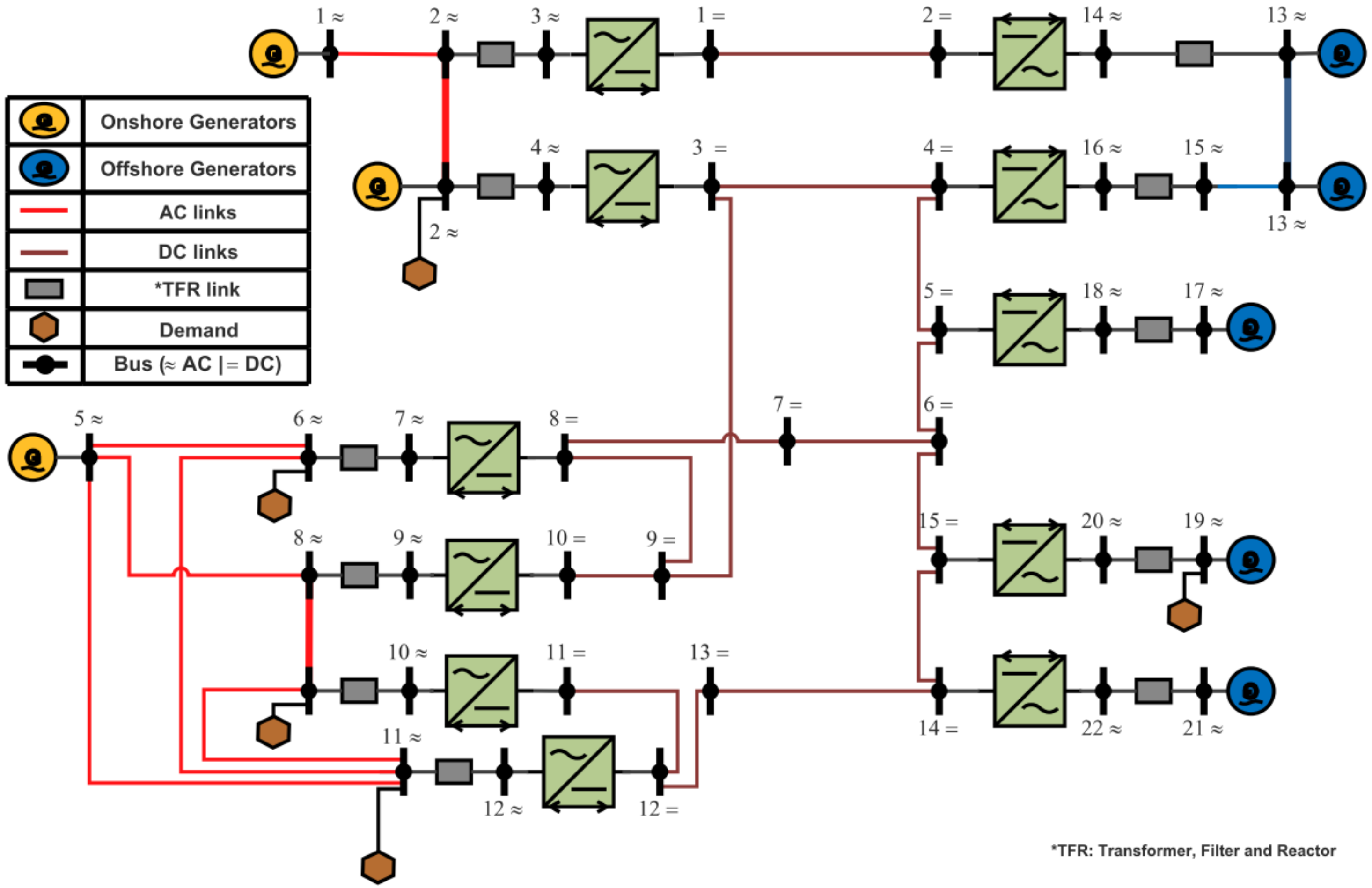
6 AC systems -22 buses-

2 DC systems -15 buses-

8 AC generators

11 converters

5 demand nodes.



Simulation – Measurements and weights

Total measurements: 109

All measurements were corrupted with 3% error, except M_{factor} measurements with 1%.

Meas. Type	Count	Details
AC	6	voltages , 1 per AC system
	15 & 15	active & reactive power injection
	8 & 8	active & reactive power flow
	14	zero injection
DC	2	voltages , 1 per DC system
	11	real power injection
	4	real power flow
	4	zero injection
Conv. Power Coupling	11	power constraints, 1 per converter
Conv. Voltage Coupling	11	M_{factor}, 1 per converter

Measurement Type	Weight
voltages/angles, power coupling and zero injections constraints	1×10^{-6}
power flow and M_{factor}	1×10^{-5}
$\pm$ power injections	1×10^{-4}

Simulation – Prepare Noisy Meas.

The noisy measurements are generated based on the below equations:

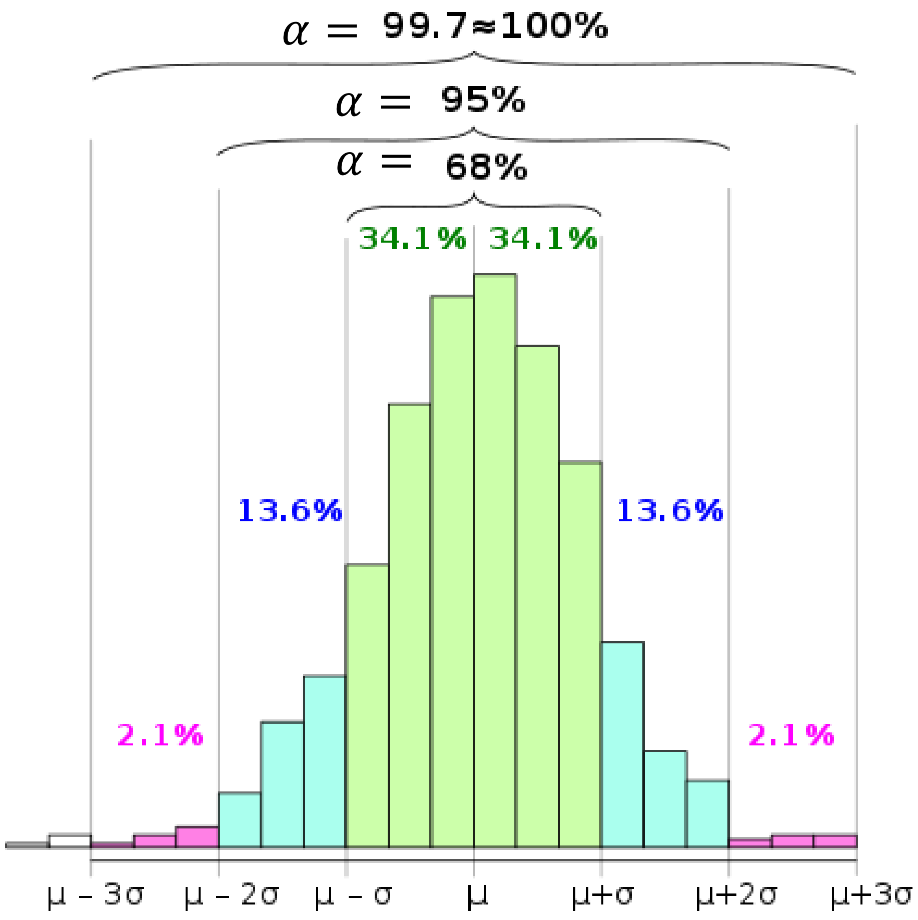
$$z_{noisy} = z_{true} + \varepsilon = z_{true} + N(\mu, \sigma^2)$$

Where z_{true} measurements are provided by a powerflow solver, and $N(\mu, \sigma^2)$ is a Gaussian noise generator.

The error (ε) is ±3σ deviation around the true measurements (μ), which covers more than 99.7% (α) area of the Gaussian curve [4]. Therefore:

$$\boldsymbol{\sigma} = \frac{\mu \times \varepsilon}{\varphi^{-1}\left(\frac{1+\alpha}{2}\right) \times 100} = \frac{\mu \times \varepsilon}{\varphi^{-1}\left(\frac{1+0.9973}{2}\right) \times 100} = \frac{\mu \times \%error}{3 \times 100}$$

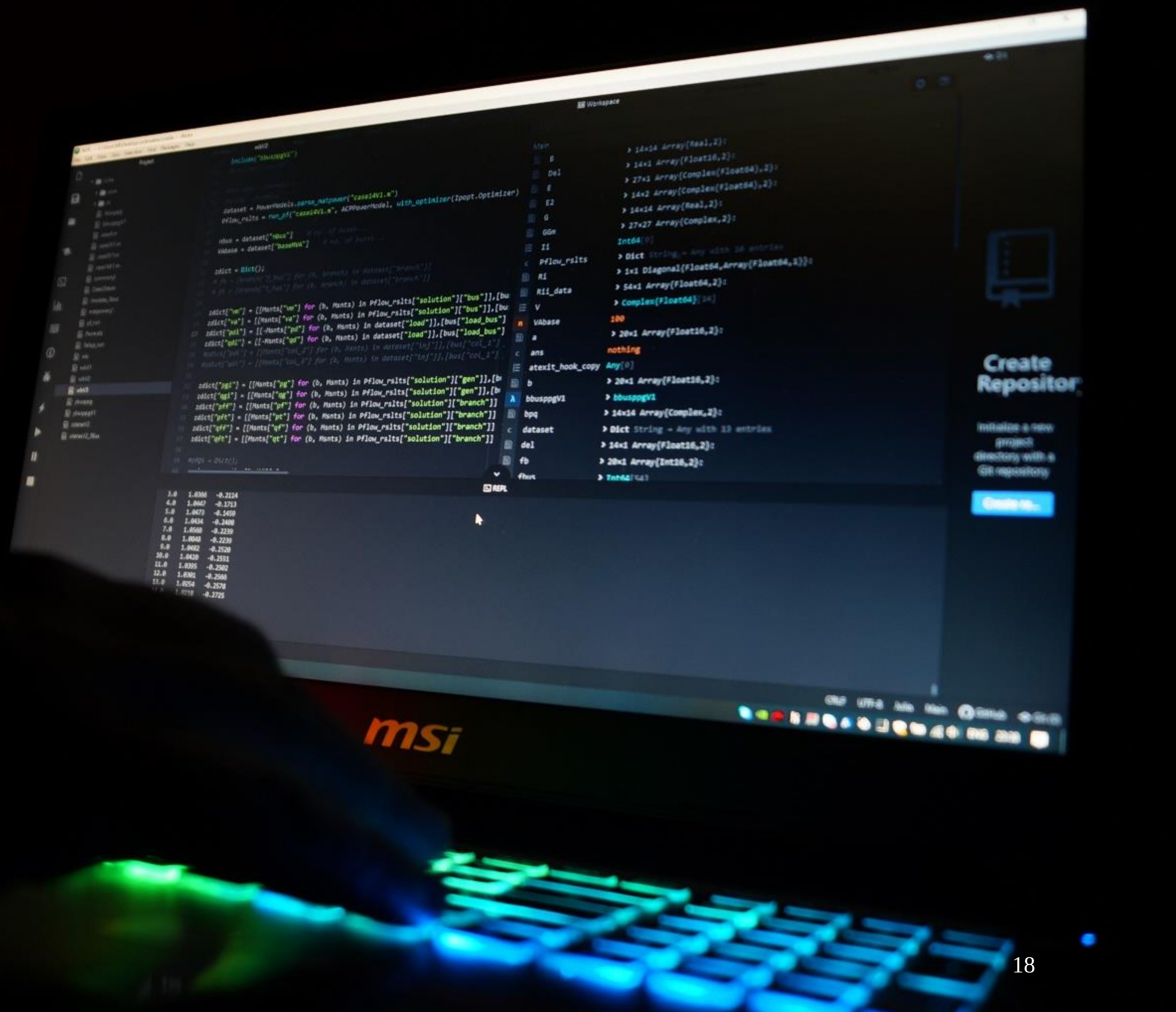
$\%error$ can be %1 or %3



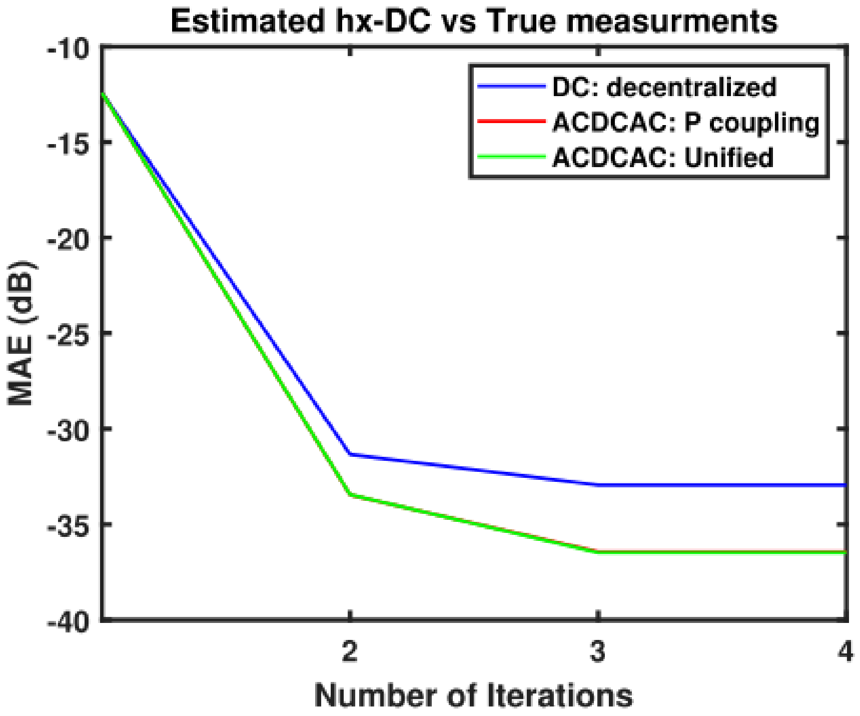
- Wikipedia

[4] - State Estimation in Power Distribution Network Operation. PhD Thesis, Imperial College London

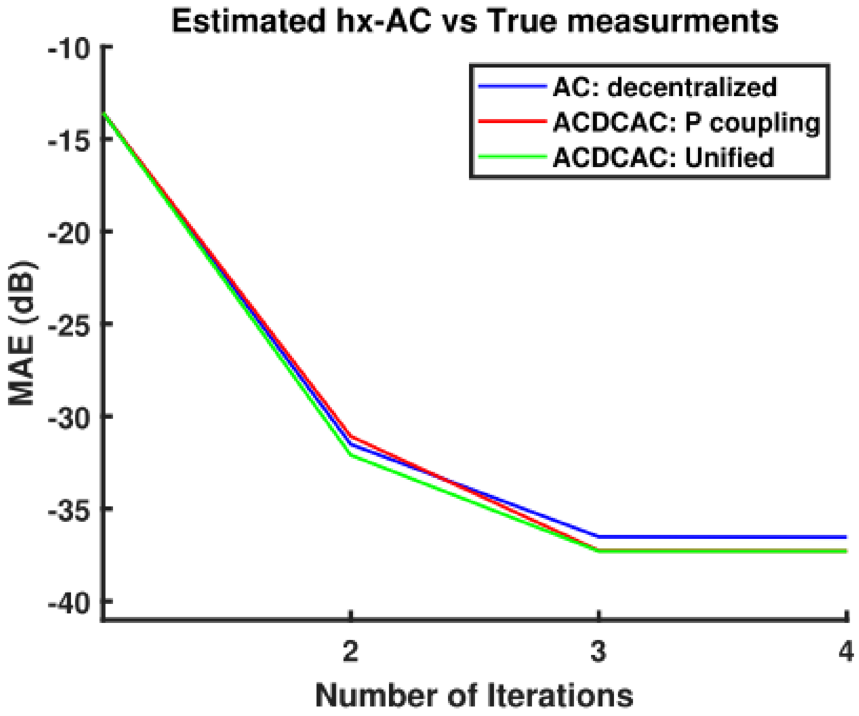
Running
simulations
- Julia



Measurments Results - MAE



(a) DC measurments



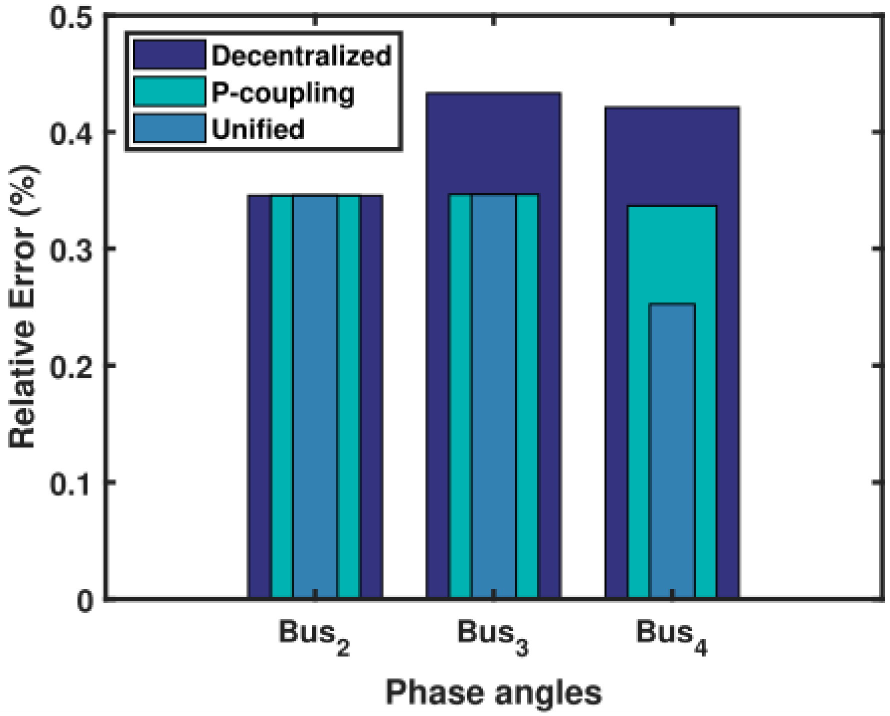
(b) AC measurments

The MAE has reduced by −3.5393 dB and −0.7577 dB respectively

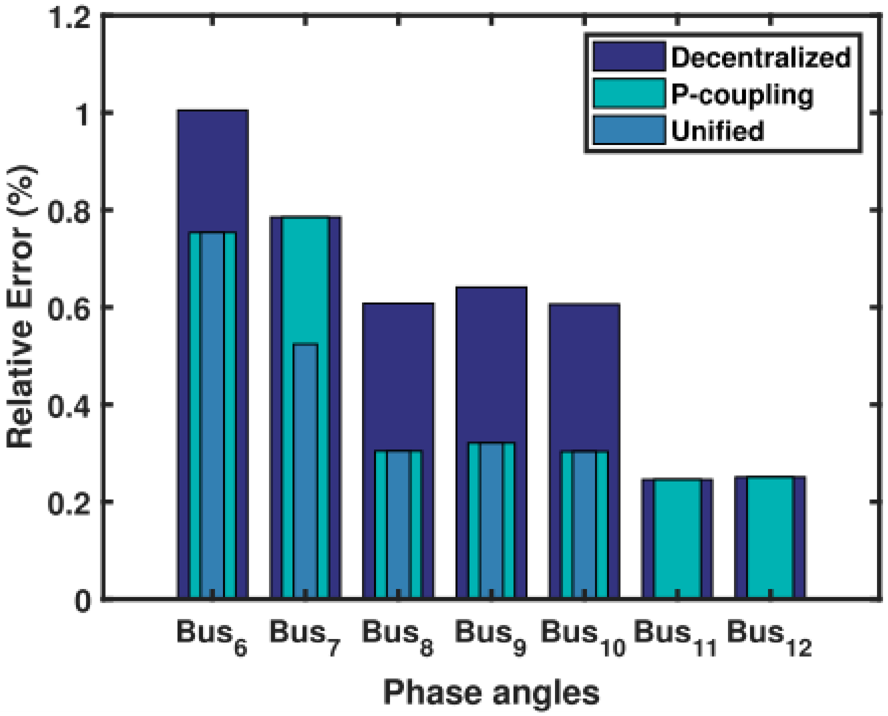
DC Systems – Voltage States Results

Sys. #	Bus #	V_{True}	$V_{Est_{T1}}$	$V_{Err_{T1}}$	$V_{Est_{T2}}$	$V_{Err_{T2}}$	$V_{Est_{T3}}$	$V_{Err_{T3}}$
1	1.0	1.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000
	2.0	1.0007	1.0007	0.0000	1.0007	0.0000	1.0007	0.0000
2	3.0	1.0100	1.0100	0.0000	1.0100	0.0000	1.0100	0.0000
	4.0	1.0100	1.0100	0.0000	1.0100	0.0000	1.0100	0.0000
	5.0	1.0094	1.0094	−0.0000	1.0094	−0.0000	1.0094	−0.0000
	6.0	1.0079	1.0078	−0.0001	1.0079	−0.0000	1.0079	−0.0000
	7.0	1.0073	1.0073	−0.0000	1.0073	−0.0000	1.0073	−0.0000
	8.0	1.0062	1.0062	0.0000	1.0062	0.0000	1.0062	0.0000
	9.0	1.0061	1.0061	−0.0000	1.0061	−0.0000	1.0061	−0.0000
	10.0	1.0020	1.0020	−0.0000	1.0020	−0.0000	1.0020	0.0000
	11.0	1.0006	1.0005	−0.0001	1.0006	−0.0000	1.0006	0.0000
	12.0	1.0006	1.0005	−0.0001	1.0006	−0.0000	1.0006	0.0000
	13.0	1.0034	1.0033	−0.0001	1.0034	−0.0000	1.0034	0.0000
	14.0	1.0054	1.0053	−0.0001	1.0054	−0.0000	1.0054	0.0000
	15.0	1.0065	1.0065	−0.0000	1.0065	−0.0000	1.0065	−0.0000

AC Systems – Phase States Results - Part

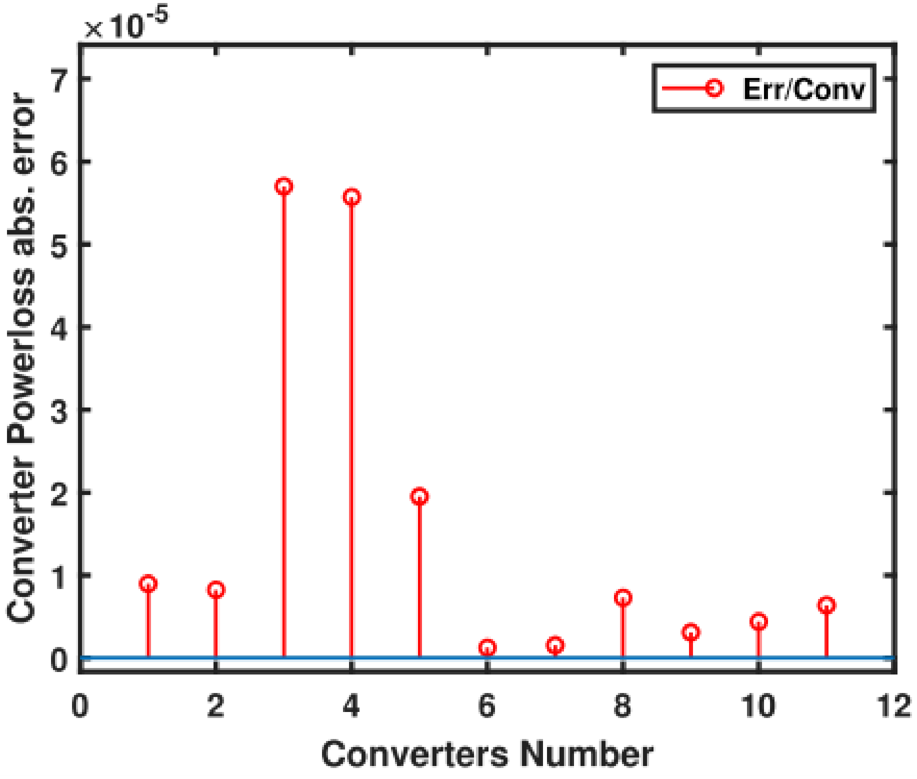


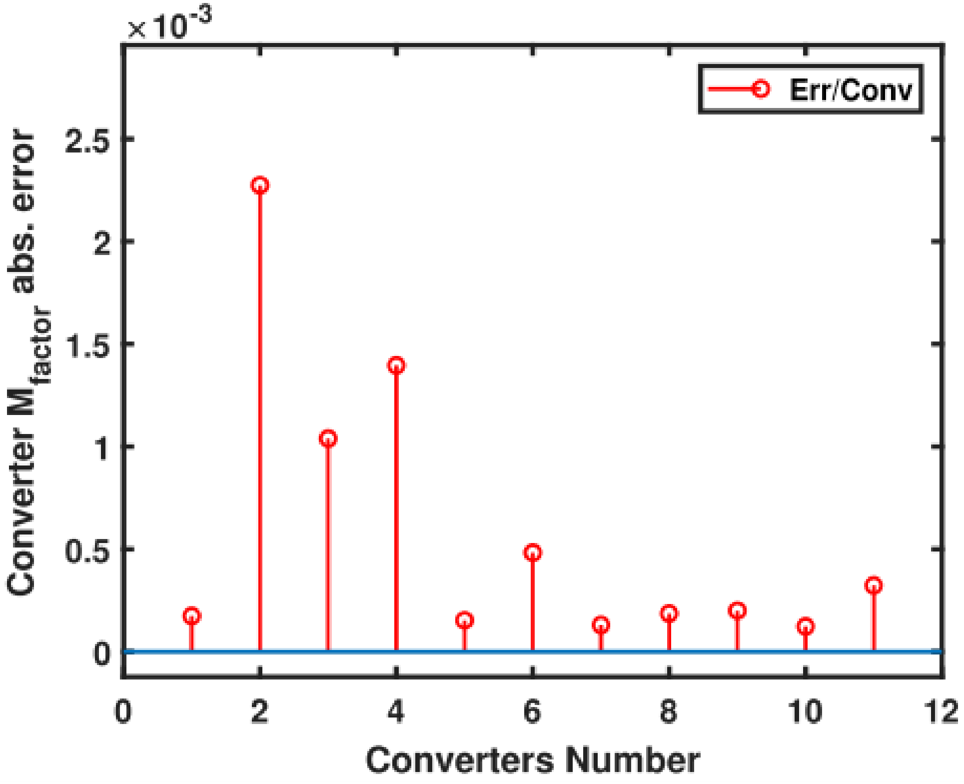
(**a**) AC system #1



(**b**) AC system #2

Unified SE – PV-Coupling Results

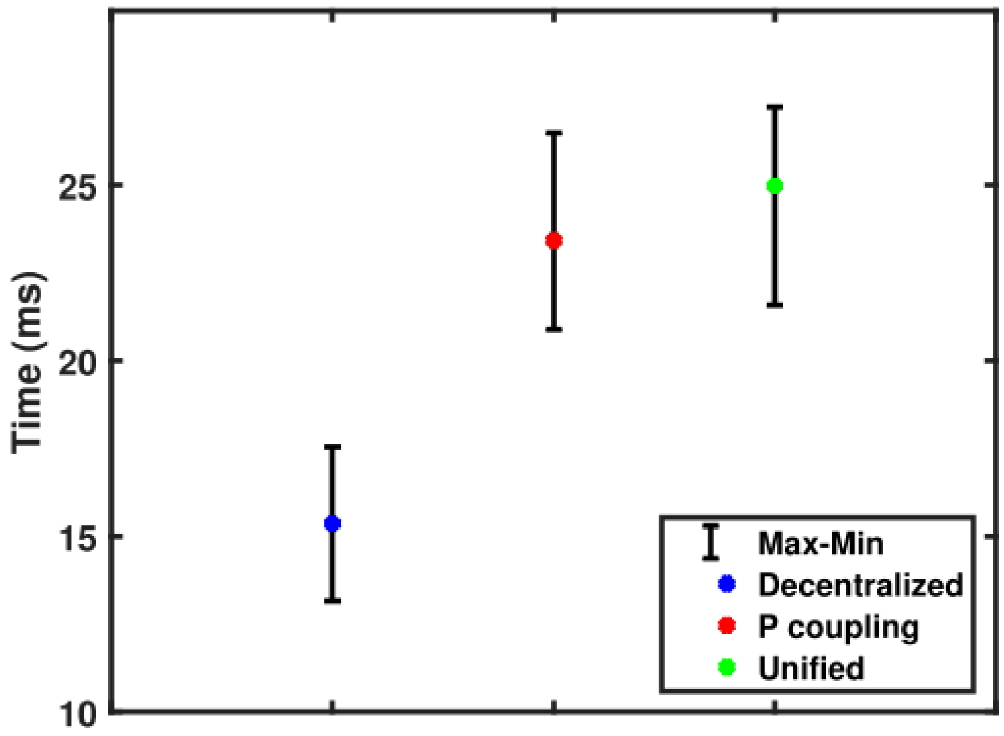




State Estimation – Results

- The time performance of the three scenarios was calculated for 100 simulations on Cigre B4 test case.

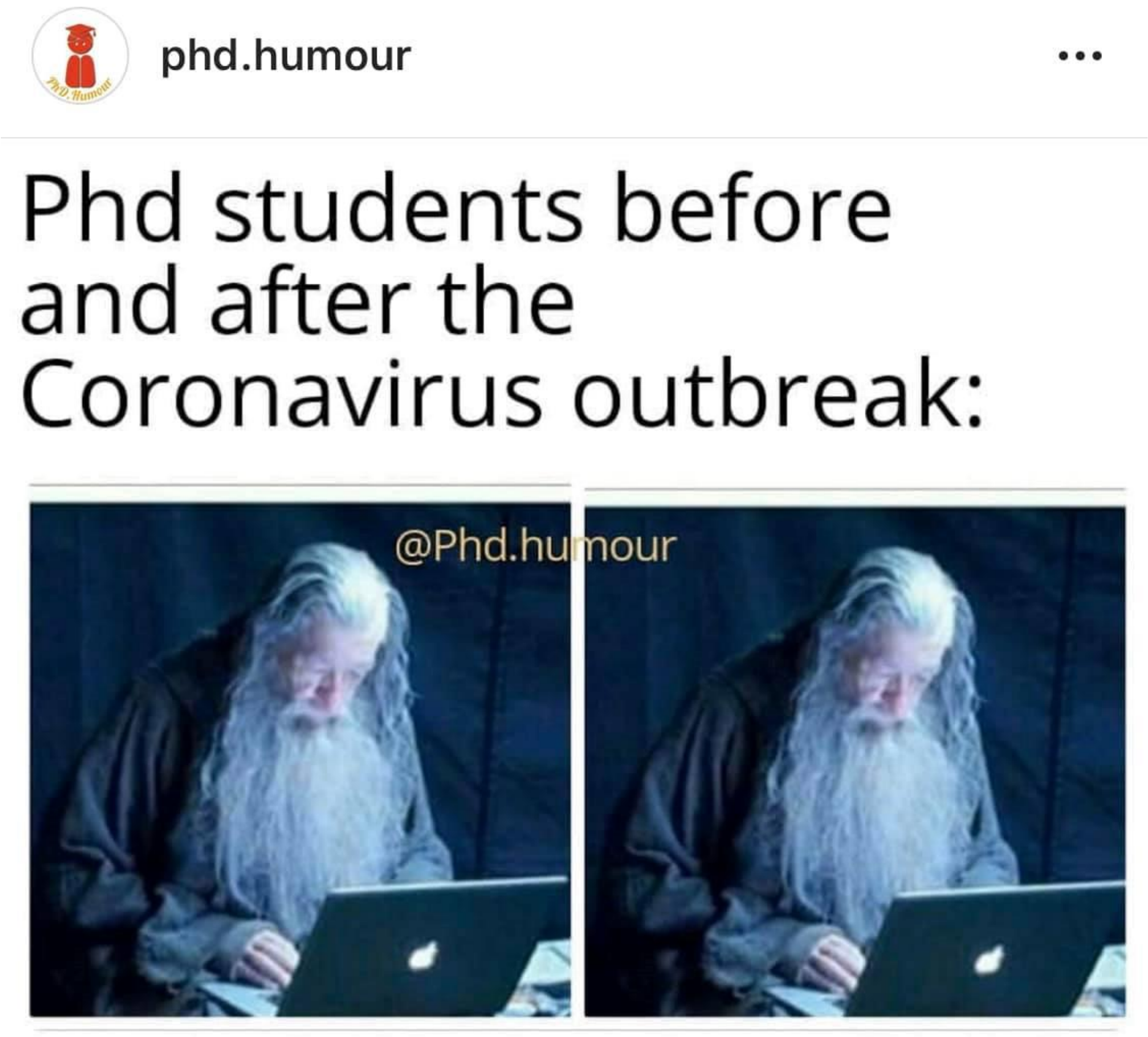
- It was concluded that the unified WLS time performance was a downside for this approach. The figure shows that the unified approach is 62% slower than the decentralized method.



State Estimation – Further details

Further details can be found in the following paper:

Ayiad, M.; Leite, H.; Martins, H. State Estimation for Hybrid VSC Based HVDC/AC Transmission Networks. *Energies* **2020**, *13*, 4932.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Unified state estimation of hybrid HVDC/AC transmission networks: Time Cycle

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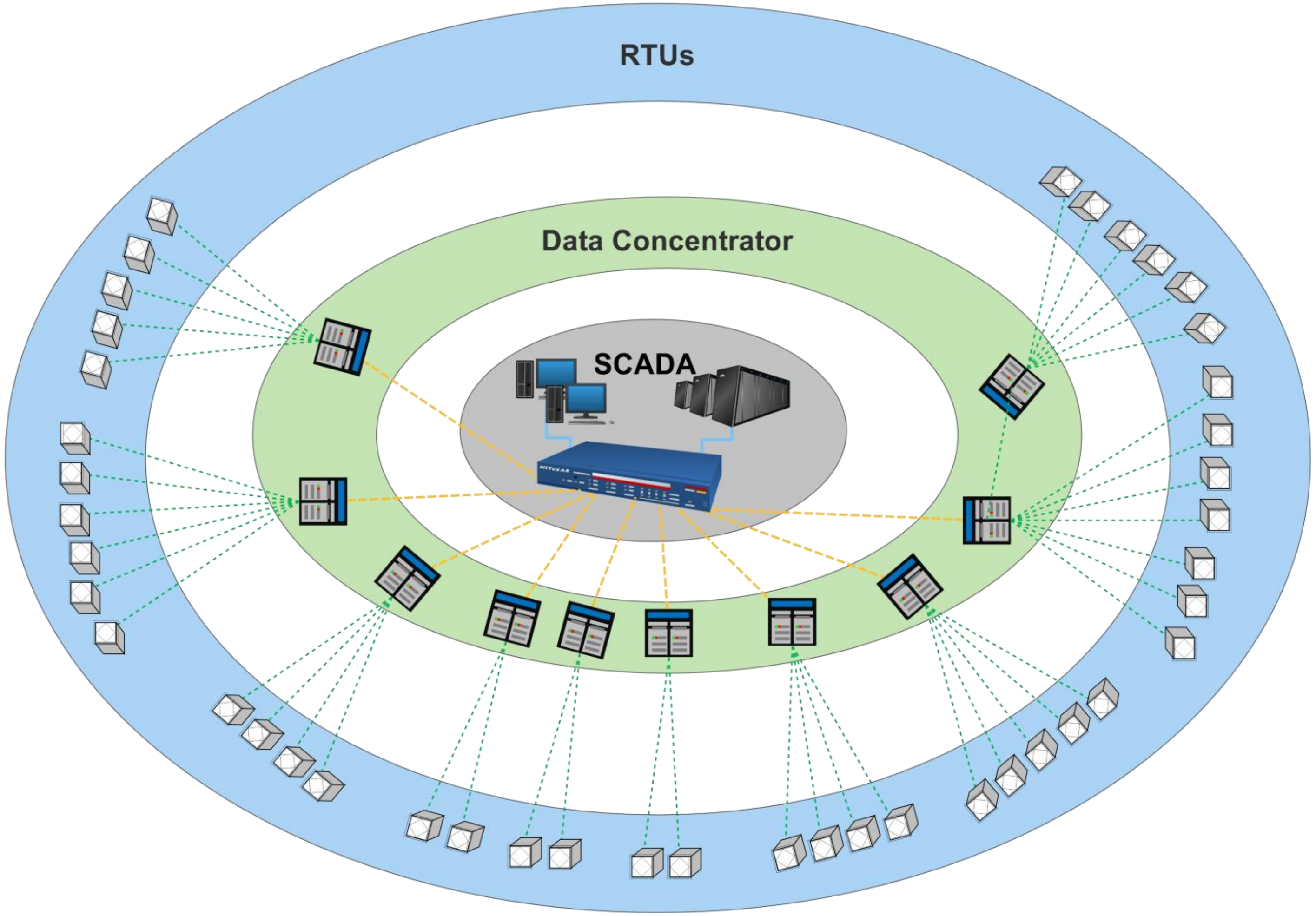
Current work – Time Cycle

- Test Case: Cigre B4, 43 RTUs, 10 data concentrators
- What is the minimum time for a complete unified AC/DC SE cycle.
- By Finding the following:
  - RTUs sensing time
  - S1 Data collection time
  - S2 Data acquisition time
  - SE Processing time



Thank you
and stay safe

Porto – Portugal
19/05/2020