Salvatore Tessitore

Detection and Measurement of inter-area oscillations for power system stability

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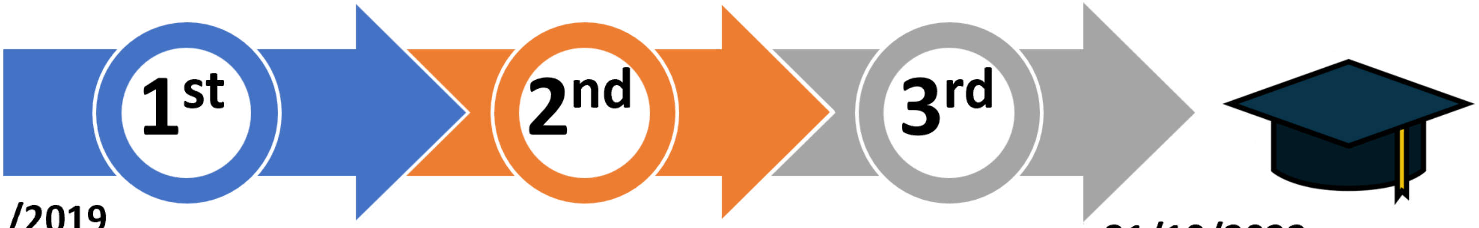
Cycle: XXXV

Year: Third

My background

- MSc degree: Electrical Engineering
- Research group: Electrical and Electronic Measurements
- PhD start date: 01/11/2019
- PhD end date: 31/10/2022
- Scholarship type: No Scholarship
- Partner company: Terna S.p.a

Summary of study activities



State of Art

Test with real signals

1/11/2019

31/10/2022

Benchmark Development

PhD Year	Courses	Seminars	Research	Tutoring / Supplementary Teaching
1st	29	5.9	35	0
2nd	13	8.2	45	0
3rd	0	0	60	0
TOTAL	42	14.1	140	0
CHECK	30-70	10-30	80-140	0-4.8

ELECTROMECHANICAL OSCILLATIONS (1/2)

Definitions

Newton Equation

$$J\omega_m \frac{d^2\delta_m}{dt^2} = P_m - P_e = P_a$$

J = moment of inerzia

ω_m = rotor speed

δ_m = load angle (position of the rotor respect to the synchronism reference)

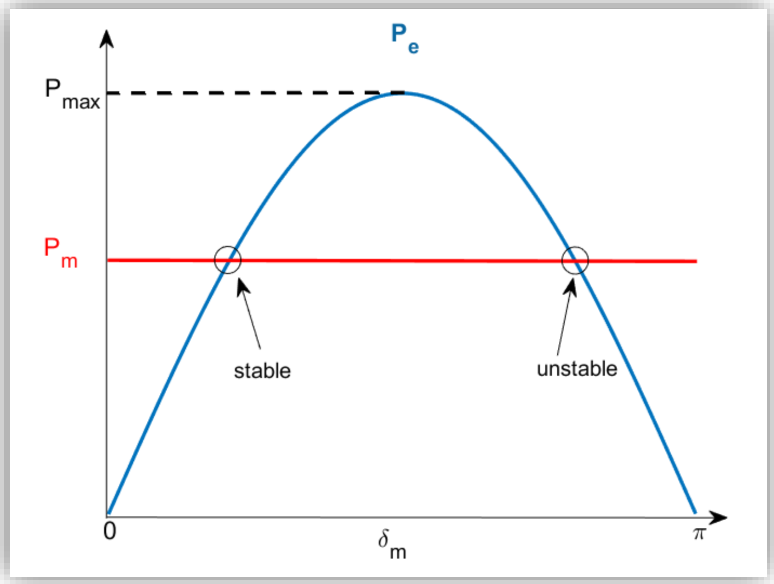
P_m = Mechanical Power

P_e = Electric power

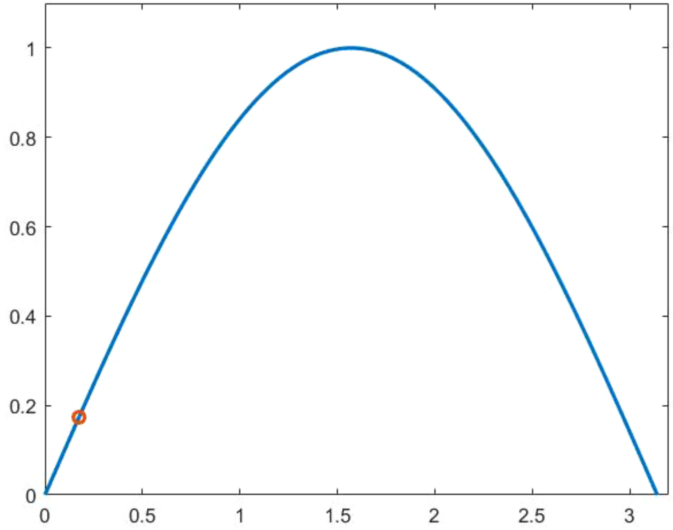
P_a = Accelerator power

Active Power

$$P_e = P_{max}\sin(\delta_m)$$



Electric power



ELECTROMECHANICAL OSCILLATIONS (2/2)

Definitions

$$X = \sum_{i=1}^{N} A_i e^{-\sigma_i t} \sin(2\pi f_i + \varphi_i)$$

- N = Oscillations number
- A_i = widht of i-th oscillation
- σ_i = damping of i-th oscillation
- f_i = frequency of i-th oscillation
- φ_i = phase of i-th oscillation

Frequency

- Local Mode $1 \text{ Hz} \leq f_i < 2 \text{ Hz}$
- Inter-area Mode $0.1 \text{ Hz} \leq f_i < 0.8 \text{ Hz}$

Damping

- Damped $\sigma_i \geq 0.05 \text{ s}^{-1}$
- Short damped $0 \text{ s}^{-1} \leq \sigma_i < 0.05 \text{ s}^{-1}$
- Divergent $\sigma_i < 0 \text{ s}^{-1}$

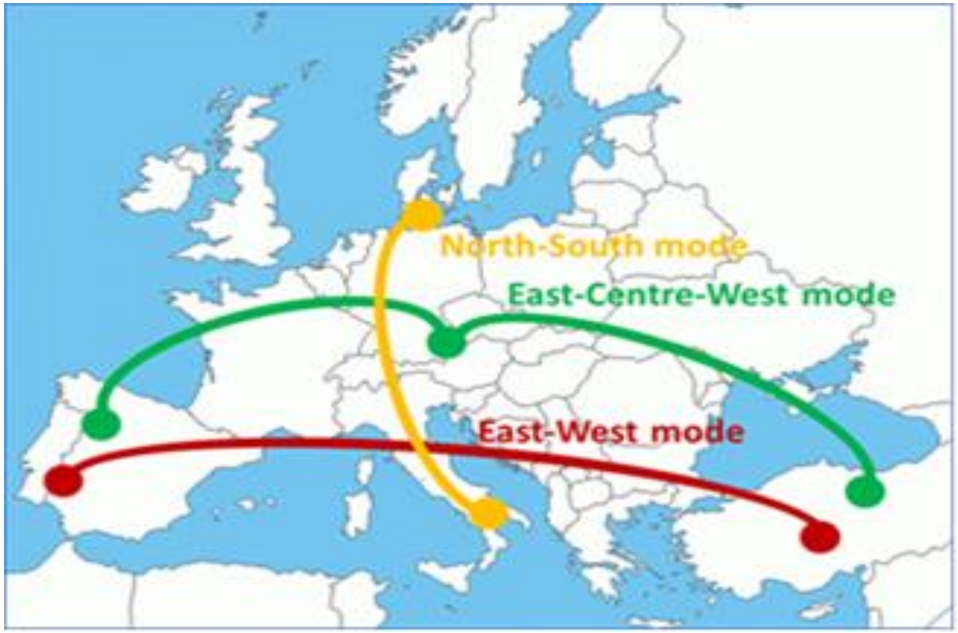
INTER-AREA OSCILLATIONS

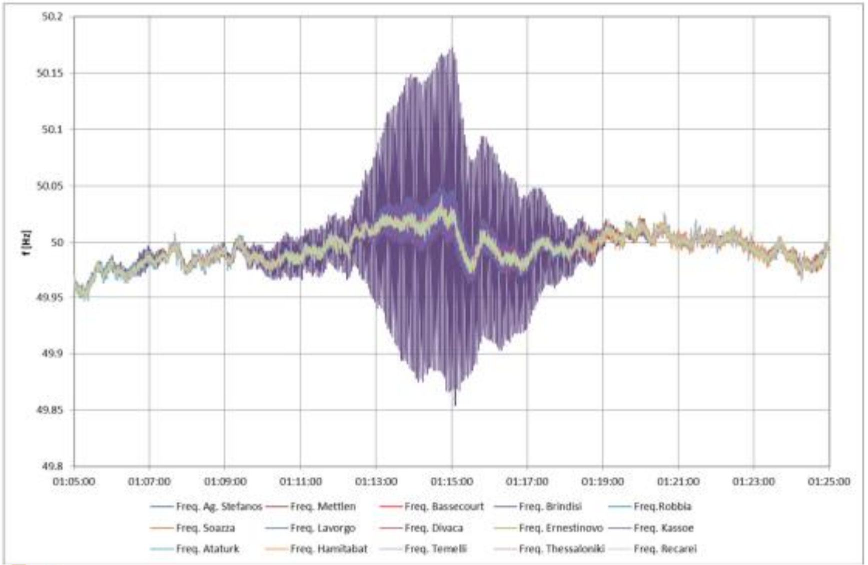
Characteristic modes

ENTSO-E Analysis

The analysis conducted in ENTSO-E show that the characteristic modes of the European electricity system are:

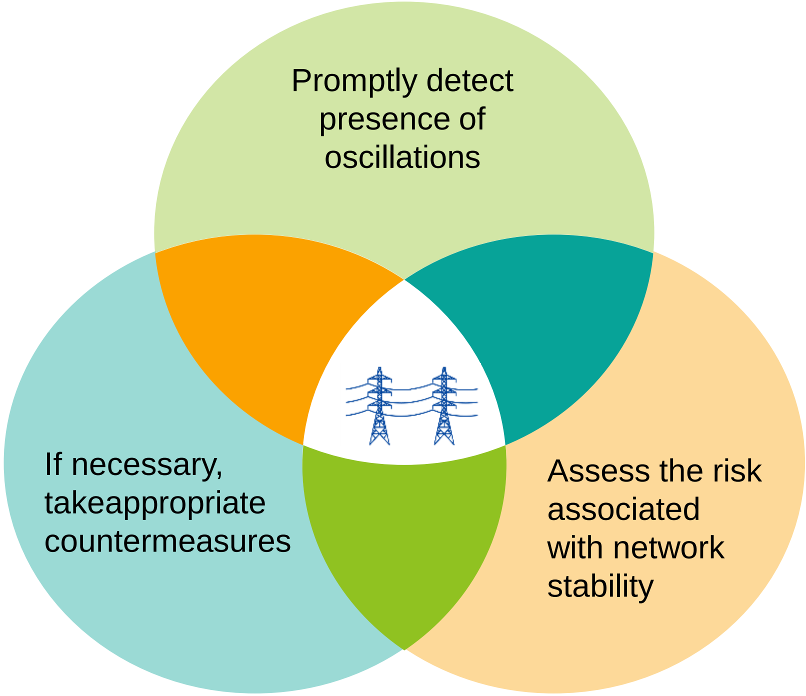
- Est-Ovest mode:
  0,13-0,15 Hz
- Est-Centro-Ovest mode:
  0,17-0,2 Hz
- Nord-Sud mode:
  0,25-0,3 Hz





Real event occurred in the European power system

Objectives

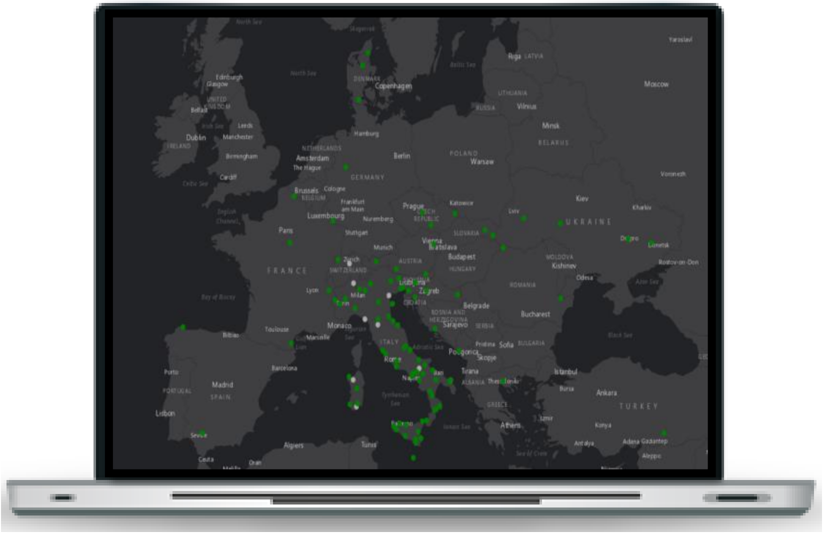


Promptly detect presence of oscillations

If necessary, takeappropriate countermeasures

Assess the risk associated with network stability

To perform these tasks, Terna monitors the grid through a **Wide Area Monitoring System (WAMS)** consisting of about 250 PMUs synchronized with each other via GPS that record the quantities of interest (such as frequency) and through appropriate calculation processes identify potentially dangerous events for the network.



ALGORITHM

Dynamic mode decomposition

The **DMD** is a modal analysis method that elaborates the frequency measurements provided by the WAMS in order to identify the main modes characterizing the state of the system. It is based on the local approximation of a dynamic system with a linear, continuous or discrete system, which can be described by the system of differential equations

$$\frac{d\mathbf{x}}{dt} = \mathcal{A}\mathbf{x}$$

Whose solution is

$$\boldsymbol{x}(t) \approx \sum_{k=1}^{n} \phi_k e^{(\omega_k t) b_k} = \boldsymbol{\Phi} e^{(\boldsymbol{\Omega} t)\boldsymbol{b}}$$

LOGICAL SEQUENCE

1. Once a sampling time Ts has been defined, the snapshots of the system state are taken

2. The acquired samples are remodeled according to the X and X 'matrix

3. It is estimated the best linear operator that minimizes the mean square error, that is the matrix A

4. Having known A, it is possible to obtain the eigenvalues and consequently the parameters characterizing the dynamic modes of the system (**frequency, amplitude, damping, phase**)

ALGORITHM

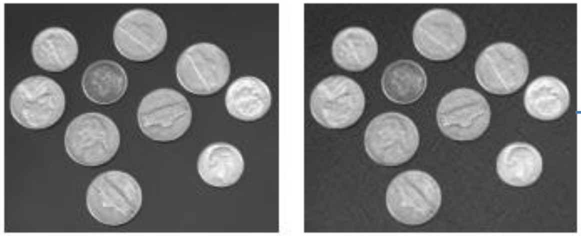
Dynamic mode decomposition

Usually, the matrix X has considerable dimensions, and it is difficult to reconstruct all the modes composing the system. Furthermore, the number of significant modes is usually low compared to the size of the matrices. We therefore do not estimate A, but a reduced-rank matrix approximating it, which is obtained through the **DECOMPOSITION TO SINGULAR VALUES or SVD**.

$$X = U\Sigma V^T \qquad \underset{(n\,x\,m)}{X} = \underset{(n\,x\,n)}{\begin{bmatrix} | & | & | \\ u_1 & .. & u_n \\ | & | & | \end{bmatrix}} \underset{(n\,x\,m)}{\begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \dots & 0 \\ 0 & 0 & \sigma_m \end{bmatrix}} \underset{(m\,x\,m)}{\begin{bmatrix} | & | & | \\ v_1 & .. & v_m \\ | & | & | \end{bmatrix}^T}$$

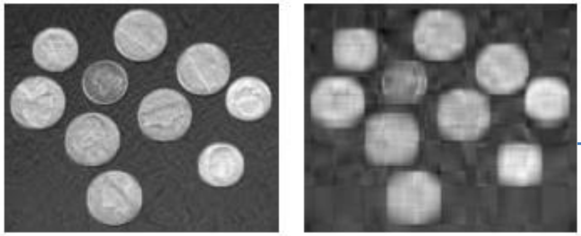
Example

Reconstruction of the matrix Σ with reduced p-rank.



(a) Immagine originale (b) p=50

the information content of the image remains intact.



(c) p=30 (d) p=10

strongly degraded image

Matrix properties U, ∑ ,V

1.Rank matrix ∑ is shown to be equal to the rank of the matrix X

2. Singolar values (elements of the **diagonal** matrix∑) are non-negative values distributed hierarchically in descending order:

$$s_i \geq 0 \quad e \quad s_i \geq s_{i+1} \quad \forall i = 1, \dots, n,$$

So is possible to fit A with a reduced-rank matrix, but it is essential to appropriately identify the proper rank.

ALGORITHM PROPOSED

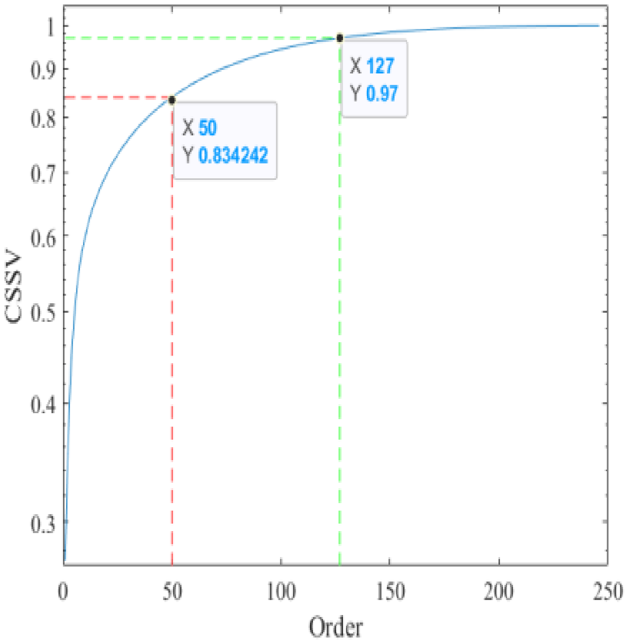
Dynamic mode decomposition with dynamic order

If the order of the DMD is established, there is a risk:

- Order too low - information loss
- Order too high - forcing the algorithm to model the system with fictitious modes

DMD with dynamic order

The dynamic order DMD, on the other hand, is able to automatically adapt the order according to the characteristics of the signal to be processed.
By diagramming the Cumulative Sum of Singular Values parameter, it can be seen that most of the information content of the previous example is concentrated in the first singular values



$$CSSV(p) = \frac{\sum_{i=1}^{p} s_i}{\sum_{i=1}^{r} s_i}$$

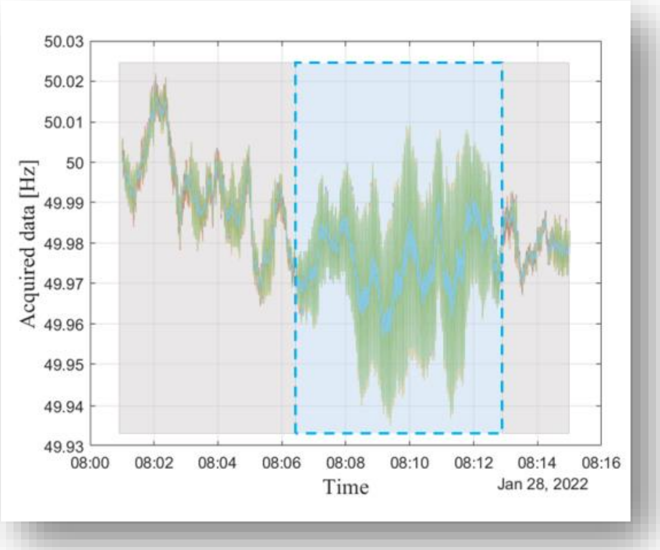
The proper rank of the dynamic matrix is established after, on the basis of singular values, imposing a threshold of the CSSV.
The choice of the threshold depends on the application. In some scenarios, for example during a network transient, the operator is interested in a particular oscillatory component; in other cases, the operator wants to observe all the components, except for the noise.

Identification of the optimal threshold was obtained through the tests carried out on actual signals

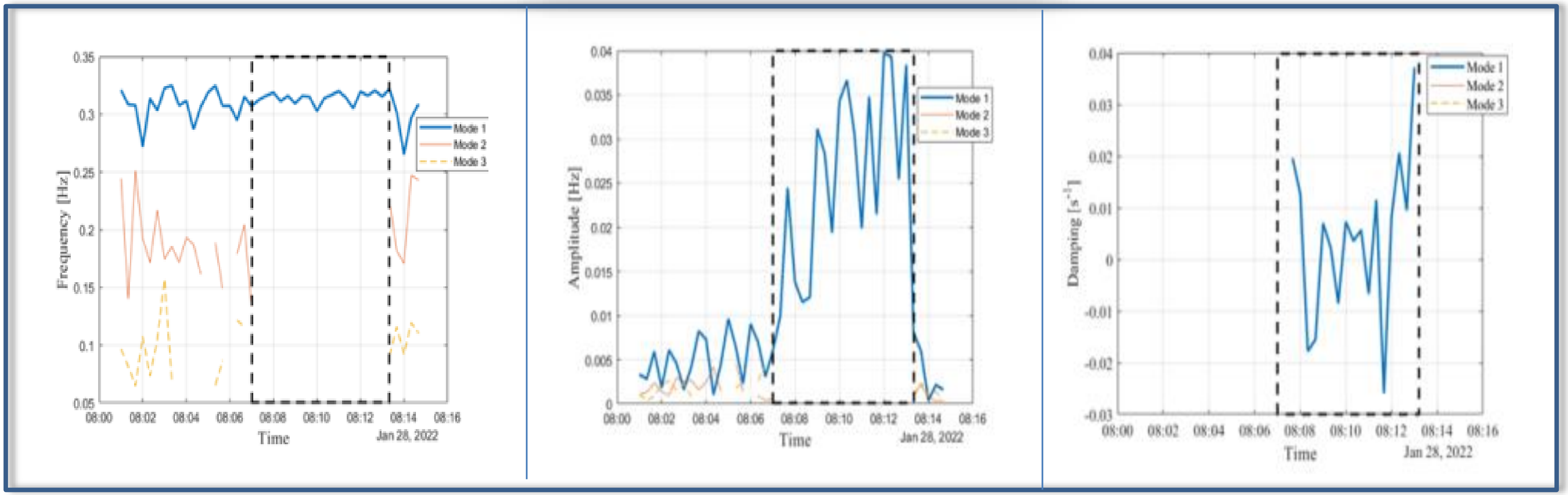
RESULTS WITH ALGORITHM PROPOSED

Dynamic mode decomposition with dynamic order

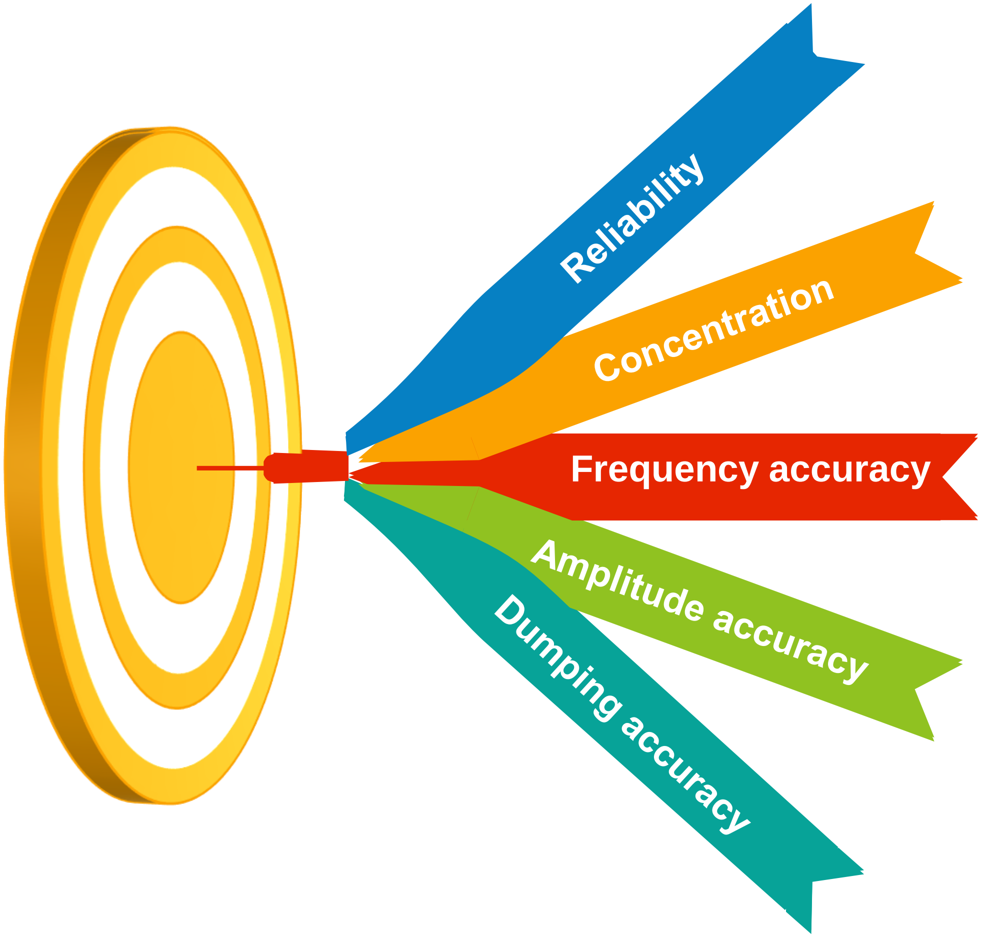
The algorithm behaves differently depending on whether it processes ambient or *transient* data



In *ambient data*, the order in which CSSV exceeds 97% can also be very high; a maximum limit of order 8 is therefore imposed



CONCLUSION



Reliability

It is more reliable than the traditional one because it is not forced to detect a predetermined number of modes

Concentration

He is able to focus on the dominant mode when there are fluctuations

Frequency accuracy

Accuracy in frequency estimation - deviation between estimated and nominal value <1%

Amplitude accuracy

Accuracy in amplitude estimation - deviation between estimated and nominal value <15%

Dumping accuracy

Accuracy in damping estimation - deviation between estimated and nominal value <30%

Research products

[P1]	Liccardo, A., Tessitore, S., Bonavolonta, F., Cristiano, S., Di Noia, L.P., Giannuzzi, G.M., Pisani, C., “Detection and Analysis of Inter-Area Oscillations Through a Dynamic-Order DMD Approach” (2022)*, IEEE Transactions on Instrumentation and Measurement, 71, art. no. 9004914*. DOI: 10.1109/TIM.2022.3186371 **International Journal IEEE Transactions on Instrumentation and Measurement**
[P2]	Liccardo, A., Bonavolonta, F., Pisani, C., Giannuzzi, G., Tessitore, S., Cristiano, S., “DMD Dynamic Order Algorithm for the Estimation of Inter-area Oscillations” (2022), *2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2022, pp. 412-417.* DOI: 10.1109/SPEEDAM53979.2022.9842132 **International Conference Symposium on Power Electronics, Electrical Drives, Automation and Motion**
[P3]	Giannuzzi, G.M., Lauria, D., Pisani, C., Tessitore, S., “An optimization procedure for power system stabilizer tuning” (2022), *2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2022, pp. 112-117.* DOI: 10.1109/SPEEDAM53979.2022.9842034 **International Conference Symposium on Power Electronics, Electrical Drives, Automation and Motion**

Research products

[P3]	Liccardo, A., Bonavolonta, F., Pisani, C., Giannuzzi, G., Tessitore, S., “Analisi delle oscillazioni inter-area tramite DMD a ordine dinamico” (2022), Atti del VI Forum Nazionale delle Misure. **National Conference VI Forum Nazionale delle Misure**

THANK YOU FOR YOUR ATTENTION

Salvatore Tessitore