SUMMER SCHOOL
"ENABLING DRES TO OFFER ANCILLARY SERVICES"
20TH – 24TH SEPTEMBER 2021

Synthetic Inertia by DRES

Dr. Georgios C. Kryonidis // 20-09-2021

This project has received funding from the European Union´s Horizon 2020 Programme for research and innovation under Grant Agreement no 764090.

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Audience Q&A Session

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Outline

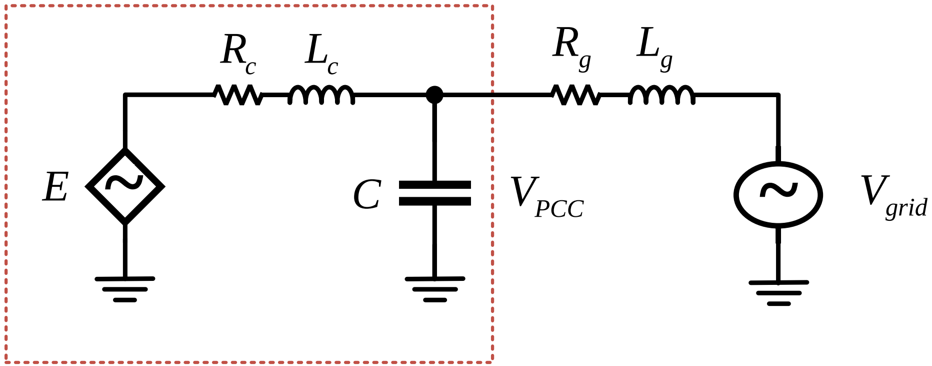
- State-of-the-art solutions
- The EASY-RES approach
- Comparative analysis
- Experimental validation
- Summary and discussion

State-of-the-art solutions

Use of the analytical synchronous generator model

Main idea: Control algorithm that imitates the behavior of a synchronous generator (SG)

Application area: Converter-interfaced renewable energy sources (CI-RES)



State-of-the-art solutions

Use of the analytical synchronous generator model

Synchronverter [1]

Damping coefficient

Reference torque

Nominal angular frequency

(1) $$\ddot{\theta} = \frac{1}{J}\left[T_m - T_e - D_p\left(\dot{\theta} - \dot{\theta}_n\right)\right]$$ **Swing Equation**

Moment of inertia

Virtual angular frequency

Electromagnetic torque

(2) $$\dot{\Phi}_{sf} = k_i^v\left(Q_{set} - Q\right)$$

Integral coefficient

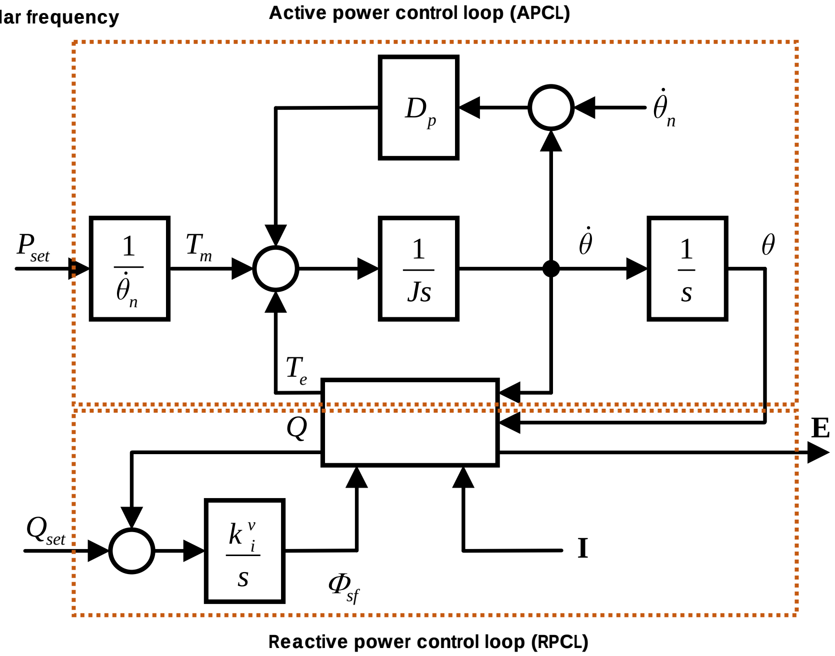
Magnetic flux

Reactive power

(3) $$T_e = \Phi_{sf}\left\langle \mathbf{I}, \sin\boldsymbol{\Theta}\right\rangle$$

(4) $$Q = -\dot{\theta}\Phi_{sf}\left\langle \mathbf{I}, \cos\boldsymbol{\Theta}\right\rangle$$

(5) $$\mathbf{E} = \dot{\theta}\Phi_{sf}\sin\boldsymbol{\Theta}$$



[1] Q. Zhong and G. Weiss, "Synchronverters: Inverters That Mimic Synchronous Generators," in IEEE Transactions on Industrial Electronics, vol. 58, no. 4, pp. 1259-1267, April 2011, doi: 10.1109/TIE.2010.2048839.

State-of-the-art solutions

Use of the analytical synchronous generator model

Synchronverter

Model parameters $\left(J, D_p, k_i^v\right)$

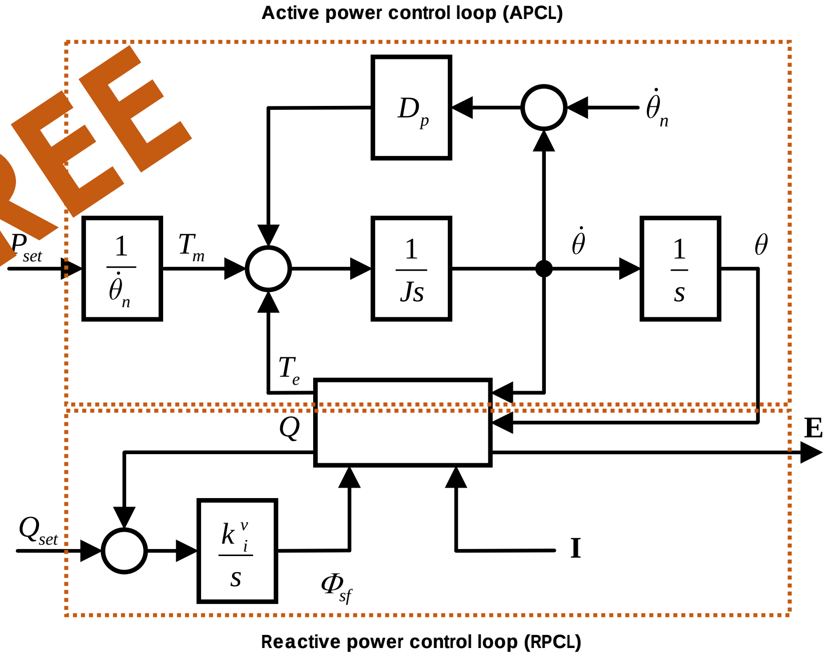
Input data $\left(P_{set}, Q_{set}, \dot{\theta}_n, \mathbf{I}\right)$

Measurement

PLL FREE

Internal variables $\left(\dot{\theta}, \Phi_{sf}\right)$

Output $\mathbf{E}$



State-of-the-art solutions

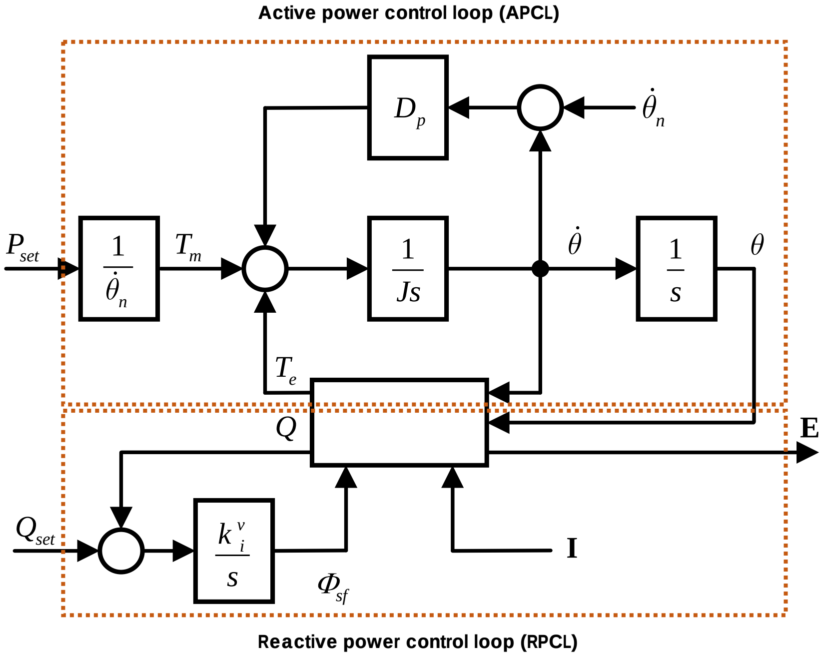
Use of the analytical synchronous generator model

Main drawbacks of the synchronverter model

Coupling between inertial (IR) and primary frequency response (PFR)

$$\ddot{\theta} = \frac{1}{J}\left[T_m - T_e - \underbrace{D_p\left(\dot{\theta} - \dot{\theta}_n\right)}_{\text{Damping}}\right]$$

Improved damping at the **expense** of PFR



State-of-the-art solutions

Use of the analytical synchronous generator model

Main drawbacks of the synchronverter model

Coupling between APCL and RPCL

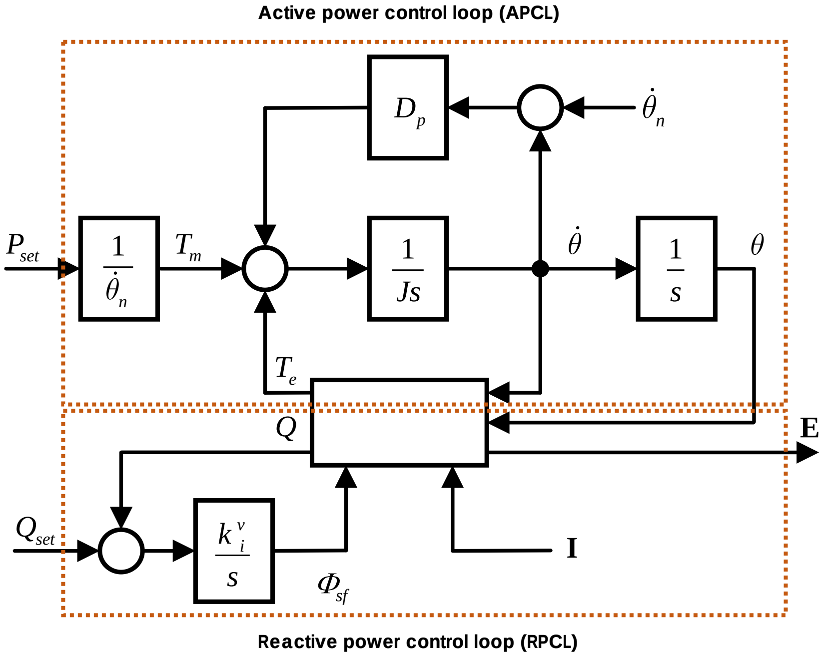
$$\ddot{\theta} = \frac{1}{J}\left[T_m - T_e - D_p\left(\dot{\theta} - \dot{\theta}_n\right)\right]$$

$$Q = -\dot{\theta}\Phi_{sf}\left\langle \mathbf{I}, \cos\mathbf{\Theta} \right\rangle$$

Mismatch between calculated and actual output active and reactive power

$$P = \dot{\theta}_n\Phi_{sf}\left\langle \mathbf{I}, \sin\mathbf{\Theta} \right\rangle$$

$$Q = -\dot{\theta}\Phi_{sf}\left\langle \mathbf{I}, \cos\mathbf{\Theta} \right\rangle$$



State-of-the-art solutions

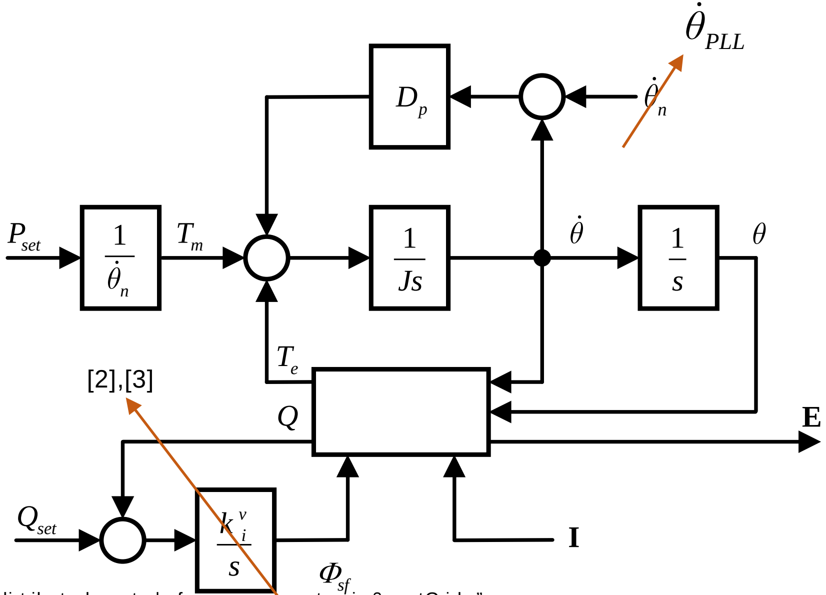
Use of the analytical synchronous generator model

Main variants of the synchronverter model

Use of a **PLL** to track network frequency [1]

$$\ddot{\theta} = \frac{1}{J}\left[T_m - T_e - D_p\left(\dot{\theta} - \cancelto{\dot{\theta}_{PLL}}{\dot{\theta}_n}\right)\right]$$

Replacing integrator in RPCL with more sophisticated control algorithms [2],[3]



Increased **complexity**

The inherent oscillatory behavior is **overlooked**

[1] S. D'Arco, J. A. Suul, and O. B. Fosso, "A Virtual Synchronous Machine Implementation for distributed control of power converters in SmartGrids," in Electric Power Systems Research, vol. 122, pp. 180-197, May 2015, doi: 10.1016/j.epsr.2015.01.001.

[2] V. Natarajan and G. Weiss, "Synchronverters With Better Stability Due to Virtual Inductors, Virtual Capacitors, and Anti-Windup," in IEEE Transactions on Industrial Electronics, vol. 64, no. 7, pp. 5994-6004, July 2017, doi: 10.1109/TIE.2017.2674611.

[3] Q. -C. Zhong, G. C. Konstantopoulos, B. Ren and M. Krstic, "Improved Synchronverters with Bounded Frequency and Voltage for Smart Grid Integration," in IEEE Transactions on Smart Grid, vol. 9, no. 2, pp. 786-796, March 2018, doi: 10.1109/TSG.2016.2565663.

Use of the analytical synchronous generator model

Main variants of the synchronverter model

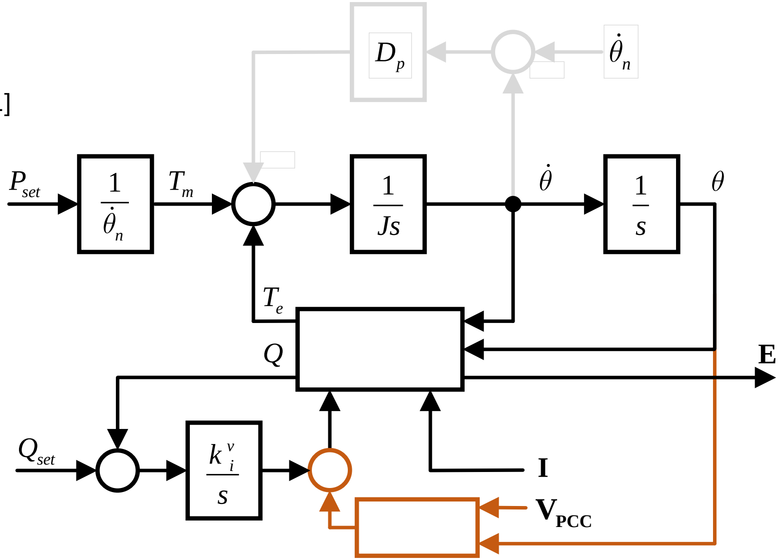
Introduce damping at the voltage magnitude [1]

Damping coefficient

(1) $$V_{dmp} = -\frac{2}{3} D \frac{d}{dt}\left(\left\langle \mathbf{V}_{\mathbf{PCC}}, \cos \mathbf{\Theta} \right\rangle\right)$$

Increased coupling between APCL and RPCL

Limited controllability of the dynamic behavior



[1] M. Ebrahimi, S. A. Khajehoddin and M. Karimi-Ghartemani, "An Improved Damping Method for Virtual Synchronous Machines," in IEEE Transactions on Sustainable Energy, vol. 10, no. 3, pp. 1491-1500, July 2019, doi: 10.1109/TSTE.2019.2902033.

State-of-the-art solutions

Use of a simplified swing equation

Conventional

Feedback signal

$$\ddot{\theta} = \frac{1}{J}\left[T_m - T_e - D_p\left(\dot{\theta} - \dot{\theta}_n\right)\right]$$

Output

Simplified

Feedback signal

$$P_e = P_m - J\ddot{\theta}$$

Output

Inertia constant (in s)

$$p_e = p_m - 2H \cdot ROCOF \qquad \text{(in pu)}$$

$$\frac{df}{dt}$$

Controls the **internal voltage**

No PLL is needed

Provision of **“true”** inertia

Coupling between IR and PFR

Controls the **output power**

Accurate measurement of the *ROCOF* (***challenging***)

PLL is ***needed***

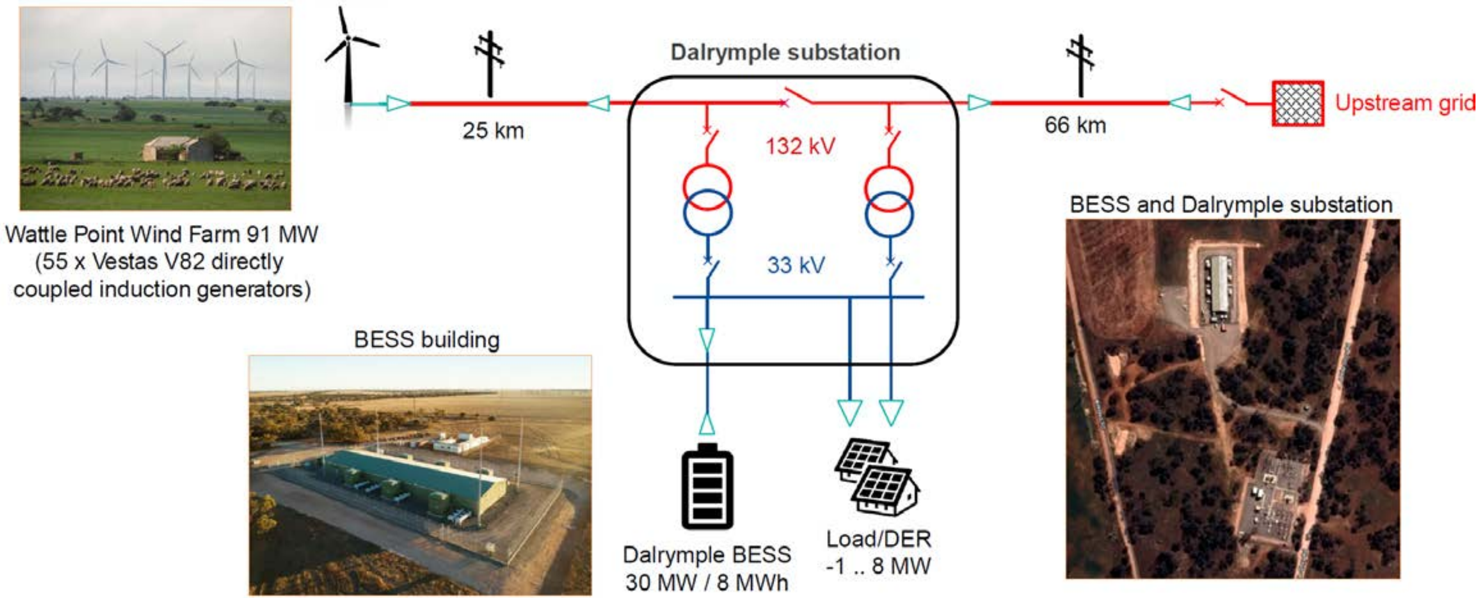
No “true” inertia provision due to the **time delay** introduced by the calculation of ROCOF

No coupling between IR and PFR

State-of-the-art solutions

Commercially Available Products

e-mesh™ PowerStore™ by Hitachi-ABB [1]



[1] https://www.hitachiabb-powergrids.com/offering/product-and-system/energystorage/powerstore

State-of-the-art solutions

Commercially Available Products

e-mesh™ PowerStore™ by Hitachi-ABB [1]

The conventional swing equation is used [2]

SVC Plus Frequency Stabilizer by Siemens Energy [3]

The simplified swing equation is employed

Wind turbine inertia control system by Siemens Gamesa [4]

The simplified swing equation is employed

[1] https://www.hitachiabb-powergrids.com/offering/product-and-system/energystorage/powerstore

[2] A. Tuckey and S. Round, "Practical application of a complete virtual synchronous generator control method for microgrid and grid-edge applications," 2018 IEEE 19th Workshop on Control and Modeling for Power Electronics (COMPEL), 2018, pp. 1-6, doi: 10.1109/COMPEL.2018.8459987.

[3] Siemens Energy, "SVC PLUS Frequency Stabilizer," https://www.siemens-energy.com/global/en/offerings/power-transmission/portfolio/flexible-ac-transmission-systems/svcplus-frequency-stabilizer.html

[4] F. Jimenez Buendia, "Wind turbine inertia control system," Europe, Patent No. EP2918824A1.

The EASY-RES approach

Unified Virtual Synchronous Generator (UVSG)

Motivation: Provide **“true”** IR decoupled from PFR with **limited** model complexity

Proposed model [1]

Modification 1: Introduction of a proportional-integral (PI) controller

Modification 2: Decoupling APCL from RPCL

Modification 3: Calculation of the active and reactive power injected to the grid

[1] J. M. Mauricio et al., “EASY-RES Deliverable D2.3: Development of dynamic functionalities of the DRES/DBESS,” pp. 1–85, 2019. [Online]. Available: https://cordis.europa.eu/project/id/764090/results

The EASY-RES approach

Unified Virtual Synchronous Generator (UVSG)

Proposed model [1]

$$\approx \frac{3EV_{PCC}}{2X_c}\left(\omega-\omega_g\right)$$

not directly measured

(1) $\ddot{\theta} = k_i^f\left(P_{set}-P\right) - k_p^f\dot{P}$

IR coefficient

damping

(2) $\dot{E} = k_i^v\omega_n\left(Q_{set}-Q\right)$

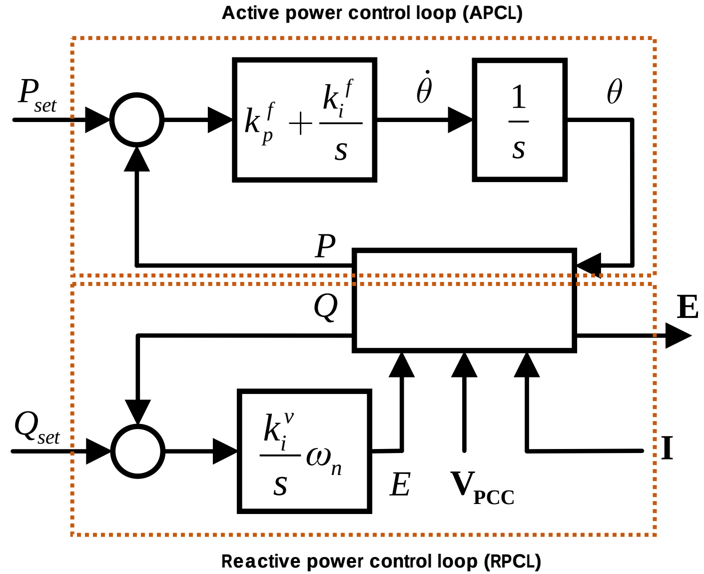
constant

(3) $P = \mathbf{V}_{\mathbf{PCC}}^{\mathbf{T}}\mathbf{I}$

(4) $Q = \mathbf{V}_{\mathbf{PCC}}^{\mathbf{T}}\left(\mathbf{A}-\mathbf{B}\right)\mathbf{I}$

Calculation of output power at PCC

(5) $\mathbf{E} = E\sin\mathbf{\Theta}$



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The EASY-RES approach

Unified Virtual Synchronous Generator (UVSG)

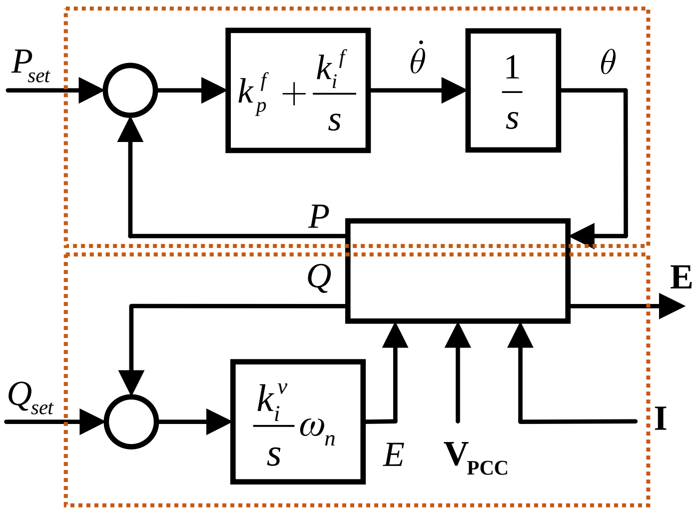
Proposed model

$\frac{1}{2H}$ $\sqrt{\frac{8X_c}{3EV_{PCC}}k_i^f}$

Model parameters	$(k_i^f, k_p^f, k_i^v, \omega_n)$
Input data	$(P_{set}, Q_{set}, \mathbf{V_{PCC}}, \mathbf{I})$
Internal variables	$(\dot{\theta}, E)$
Output	$\mathbf{E}$

Measurements

Critically damped system ($\zeta = 1$)



The EASY-RES approach

Unified Virtual Synchronous Generator (UVSG)

Maintaining the power balance in UVSG

Output power

$$p = p_m - 2H \cdot ROCOF$$

Power from the primary energy source

$$\left.\begin{aligned} ROCOF > 0 \Rightarrow p < p_m \\ ROCOF < 0 \Rightarrow p > p_m \end{aligned}\right\} \text{Power mismatch}$$

First solution: Actively control p_m to meet the desired output power p

Main drawback: The unit should operate with a headroom **below MPP** to be capable of providing **additional** power in case of **negative ROCOF,** thus leading to **loss** of green energy

Second solution: Use of **fast energy storage system (FSS)** that **absorbs** any power mismatch

Main drawback: Additional cost which is very small compared to the cost of CI-RES [1]

[1] C. S. Demoulias et al. " Ancillary Services Offered by Distributed Renewable Energy Sources at the Distribution Grid Level: An Attempt at Proper Definition and Quantification," Applied Sciences 2020, 10, 7106. https://doi.org/10.3390/app10207106.

The EASY-RES approach

Unified Virtual Synchronous Generator (UVSG)

FSS sizing for IR [1]

IR power

$$p = p_m - 2H \cdot ROCOF \Rightarrow p_{IR} = -\frac{2H}{f_N}\frac{df}{dt}$$

Nominal frequency

Frequency event at $t = t_0$. Frequency nadir at $t = t_1$

IR energy

$$e_{IR} = \int_{t=t_0}^{t=t_1} p_{IR}\,dt = -\frac{2H}{f_N}\left(f_{t=t_1} - f_{t=t_0}\right)$$

$$f_{t=t_0} = f_N$$

$$f_{t=t_1} = f_{final}$$

Independent of time !!

$$e_{IR} = -\frac{2H}{f_N}\left(f_{final} - f_N\right)$$

$$\text{in pu} \cdot \text{s or } \frac{kJ}{kW}$$

The EASY-RES approach

Unified Virtual Synchronous Generator (UVSG)

FSS sizing for IR

$$e_{IR}^{\max} = \frac{2H}{f_N}\max\left(\left|f_{final} - f_N\right|\right)$$

Maximum frequency deviation is **2.5 Hz** (**unrealistic** to assume 50 Hz)

Frequency range: **47.5 – 52.5 Hz**

Above this threshold, large power plants can be **disconnected** [1]

$$e_{IR}^{\max} = 0.1H\ \frac{kJ}{kW} \quad \text{or} \quad 0.0278H\,\frac{Wh}{kW}$$

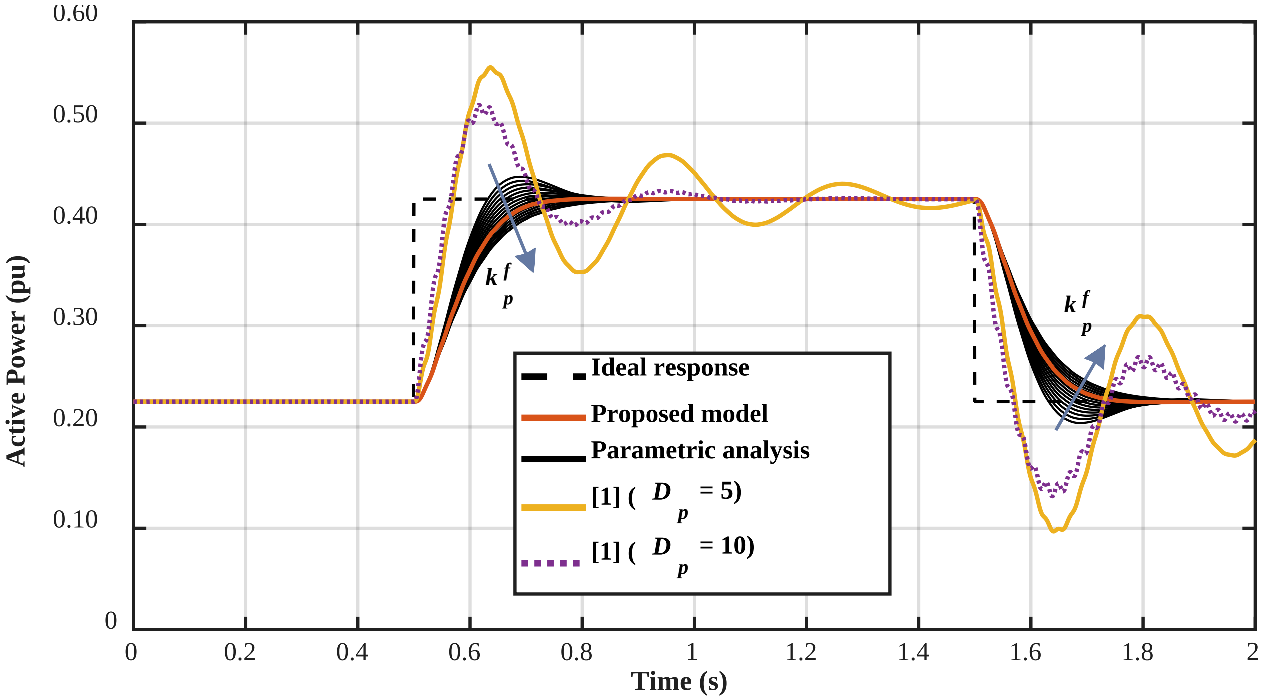
Example:

H = 5 s $\quad e_{IR}^{\max} = 0.5\ \frac{kJ}{kW} \quad \text{or} \quad 0.138\ \frac{Wh}{kW}$

[1] Greek Grid Code, Available [Online], https://www.admie.gr/en/market/regulatory-framework/esmie-operation-code.

Comparative analysis

Frequency event at 0.5 s. 50 Hz → 49 Hz in 1s



$$p_{IR} = -\frac{2H}{f_N}\frac{df}{dt} = -\frac{2\cdot 5}{50}(-1) = 0.2\,pu$$

[1] M. Ebrahimi, S. A. Khajehoddin and M. Karimi-Ghartemani, "An Improved Damping Method for Virtual Synchronous Machines," in IEEE Transactions on Sustainable Energy, vol. 10, no. 3, pp. 1491-1500, July 2019, doi: 10.1109/TSTE.2019.2902033.

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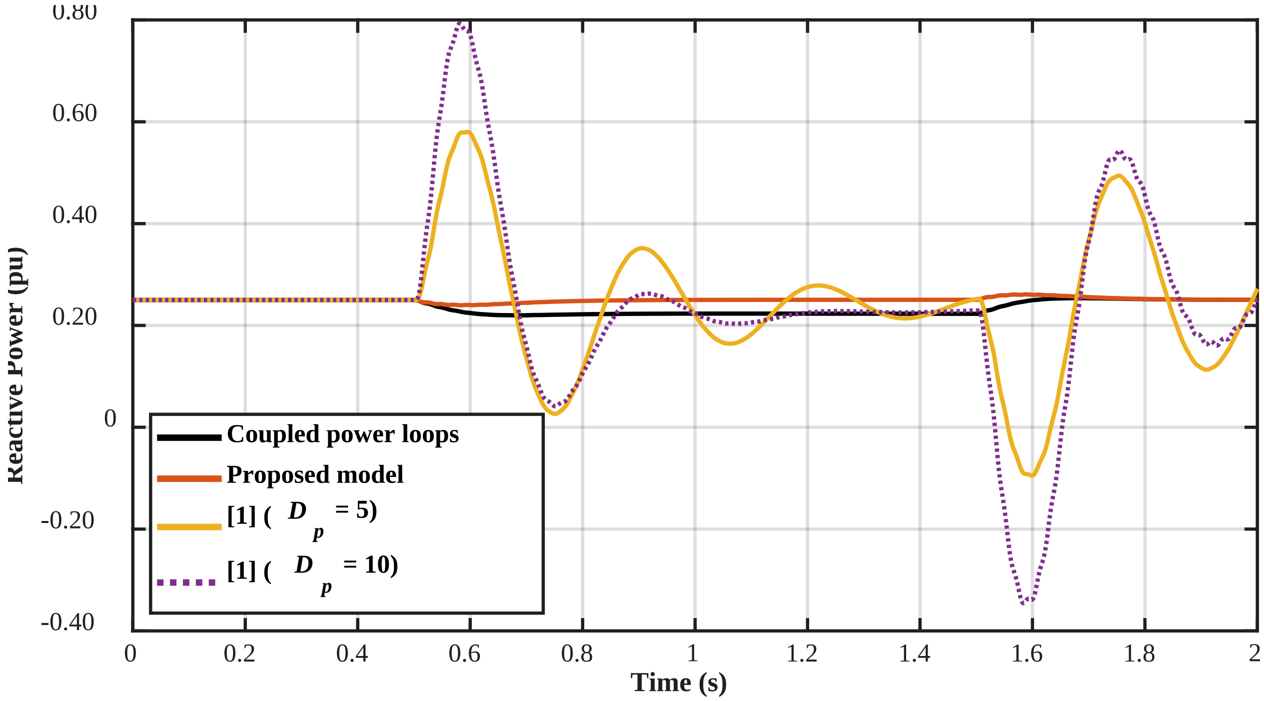

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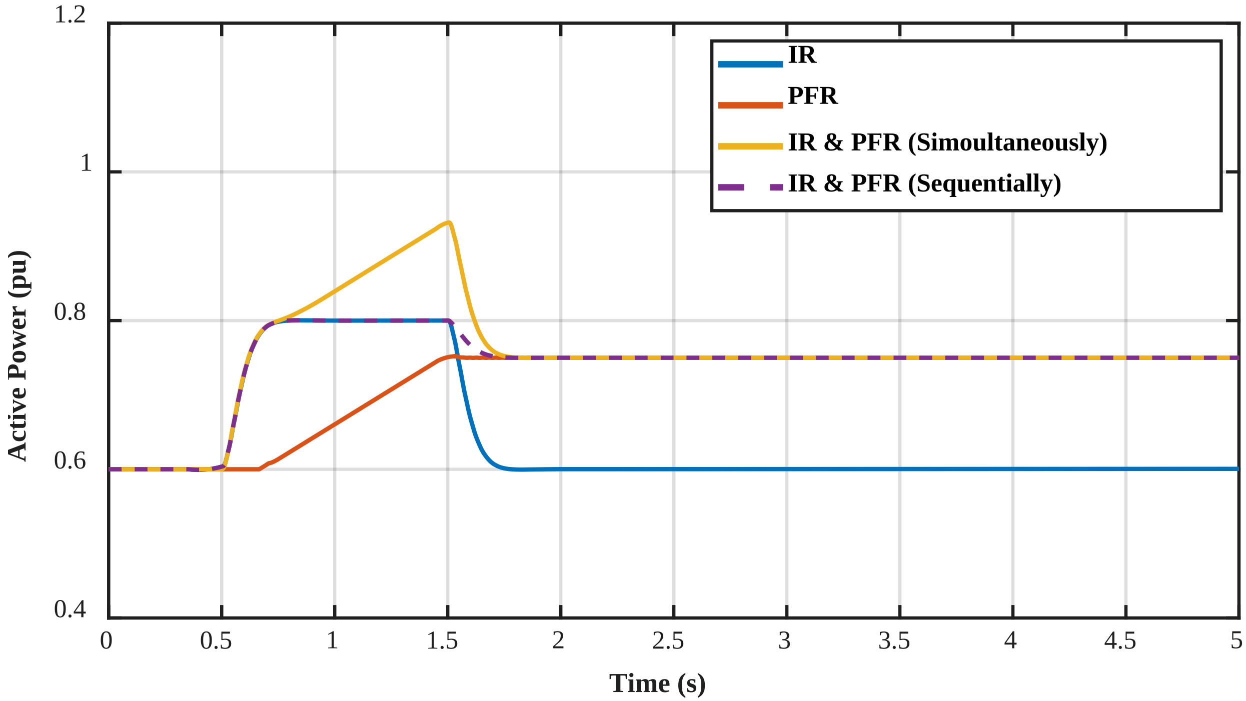

Comparative analysis

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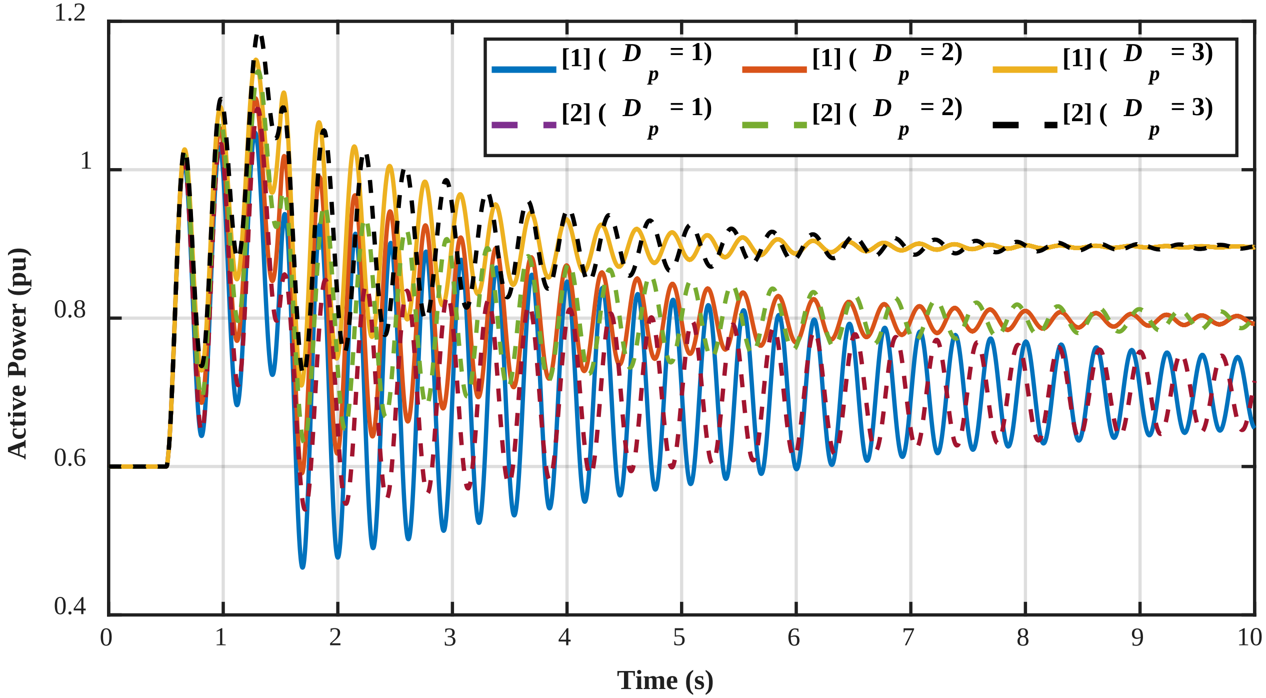

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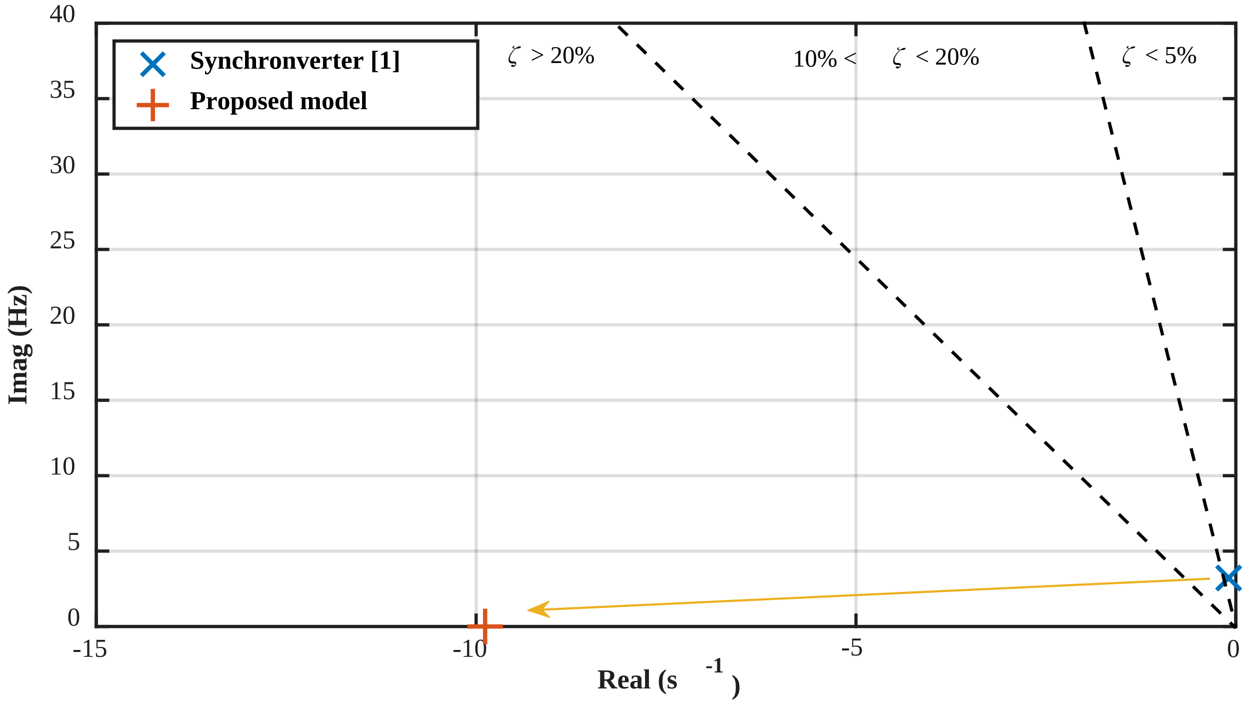
[2] V. Natarajan and G. Weiss, "Synchronverters With Better Stability Due to Virtual Inductors, Virtual Capacitors, and Anti-Windup," in IEEE Transactions on Industrial Electronics, vol. 64, no. 7, pp. 5994-6004, July 2017, doi: 10.1109/TIE.2017.2674611.

Comparative analysis

Eigenvalue analysis



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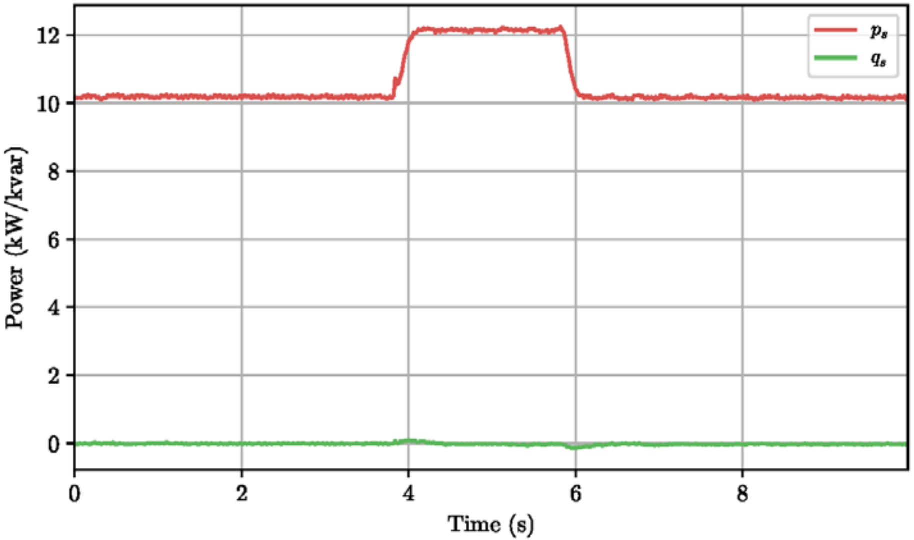
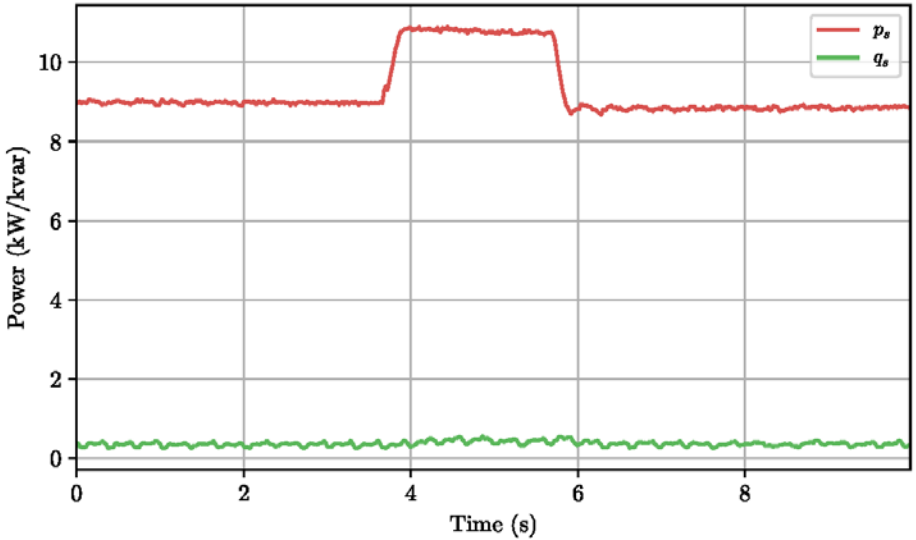
Experimental validation

$ROCOF$ = 0.5 Hz/s, S_N = 20 kVA

Infinite dc bus



Supercapacitor [1]



[1] A. M. Gross, K.-N. D. Malamaki, M. Barragan Villarejo, G. C. Kryonidis, J. L. Martinez Ramos, C. S. Demoulias, "Energy Management in Converter-Interfaced Renewable Energy Sources Through Ultracapacitors for Provision of Ancillary Services," presented in 4 th International Conference on Smart Energy Systems and Technologies (SEST 2021) pp 1-6 2021.

Summary and Discussion

Several implementations for the provision of synthetic inertia exist

Calculating ROCOF via measurements is a **challenging** task, **delaying** also the inertia provision (**not “true”** inertia)

Implementations that use the **conventional** swing-equation, e.g., synchronverter, are characterized by **poor damping** of oscillations and **coupled** IR and PFR

EASY-RES approach can **overcome** all the above-mentioned issues. **No frequency measurement** is needed. IR is **decoupled** from PFR. Thus, they can be **individually handled**, **measured**, and thus **remunerated**.

The Consortium

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Thank you!

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Audience Q&A Session

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Synthetic inertia can be provided by

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A phase-locked loop (PLL) is needed for the implementation of

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“True” inertia is provided

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The decoupling of inertial response (IR) for primary frequency response (PFR) can be implemented by

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The energy released/stored by a fast energy storage system (FSS) during a frequency event depends on

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