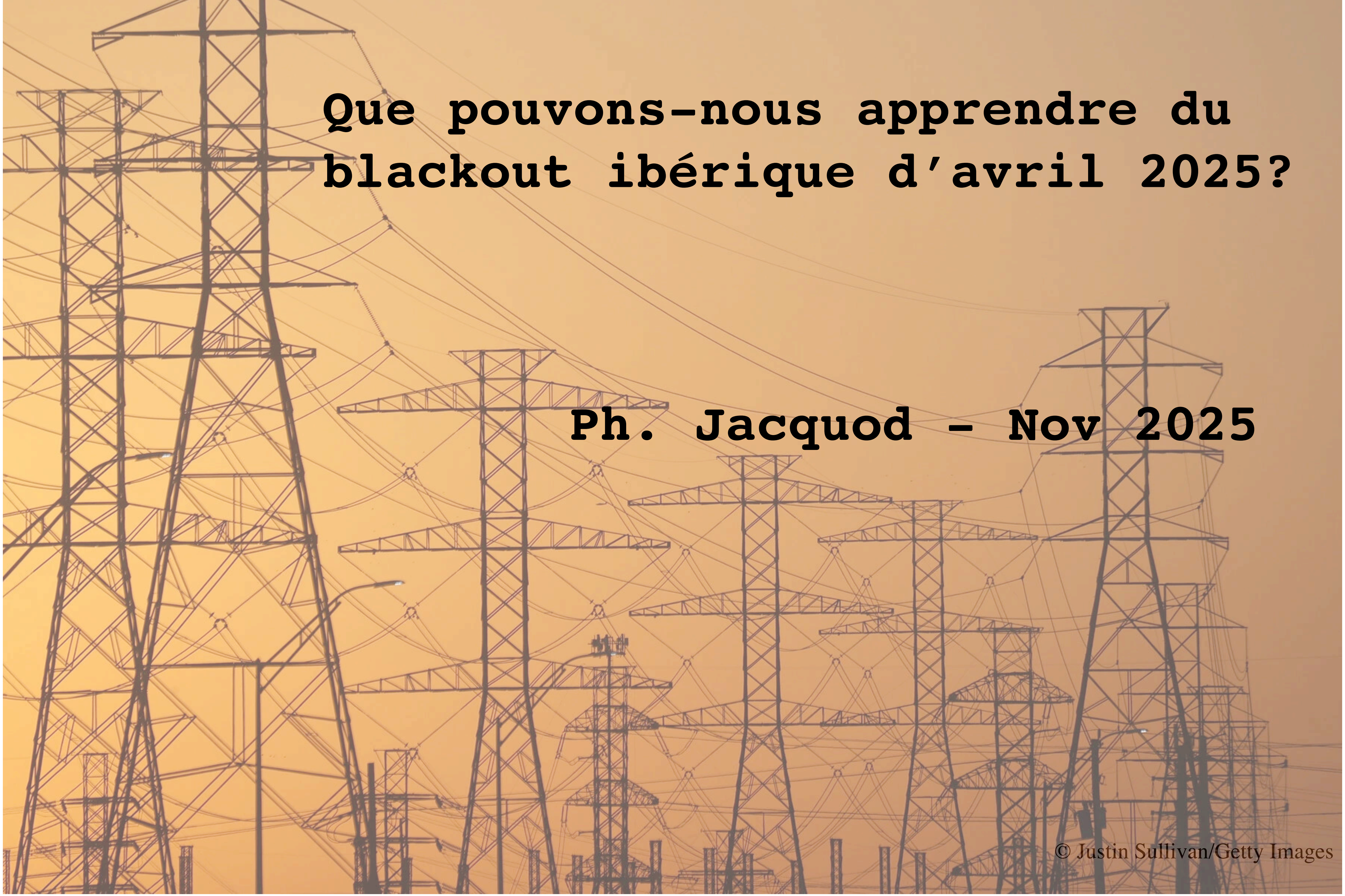
Que pouvons-nous apprendre du blackout ibérique d'avril 2025?

Ph. Jacquod – Nov 2025



UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

andlinger center
for energy+the environment

Hes·so VALAIS WALLIS
School of Engineering

Not the first time: Italy blackout of sep 2003

- **Low electric load in Italy ~27 GW**
- **Of this 6.7GW are imports**
- **Of this more than half ~3.6GW from CH**
- **Failure of Lukmanier line (flash-over)**
- **Flow on Lukmanier line ~0.8GW is redistributed which leads to overflows**
- **Failure of San Bernardino line …cascade …Italy is disconnected**

~large interconnection flows + exceptional event > grid failure

A. Berizzi, IEEE Power Engineering Society General Meeting, 2004.

OFEN Report on the blackout in Italy on 28 Sep 2003.

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Se presenta el informe del Comité de análisis de la crisis eléctrica del 28 de abril

Hoy en Consejo de Ministros

17/06/2025

El cero eléctrico se produjo por un problema de sobretensión con un origen multifactorial: el sistema contaba con una capacidad de control de tensión insuficiente, se produjeron oscilaciones que condicionaron la operación del sistema y se desconectaron instalaciones de generación, en algunos casos de un modo aparentemente indebido

El Gobierno aprobará en el próximo Consejo de Ministros un paquete de medidas para incrementar la robustez del sistema eléctrico

https://www.miteco.gob.es/es/prensa/ultimas-noticias/2025/junio/se-presenta-el-informe-del-comite-de-analisis-de-la-crisis-elect.html

VICEPRESIDENCIA TERCERA DEL GOBIERNO
MINISTERIO PARA LA TRANSICIÓN ECOLÓGICA Y EL RETO DEMOGRÁFICO

Castellano | Buscar

Ministerio Energía Medio Ambiente Reto Demográfico Servicios

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40 years
red eléctrica

Press release

The SO presents its report

Red Eléctrica presents its report on the incident of 28 April and proposes recommendations

Its conclusions show that one group incorrectly triggered generation, while another did not comply with the voltage control regulations of the P.O. 7.4.

As usual, the System Operator (SO) made the appropriate daily calculations for programming the technical restrictions, always assuming that all groups comply with the obligations imposed by the current regulations.

The SO makes 15 recommendations, especially the implementation of a dynamic voltage control service that covers all generation activities.

Madrid, 18 June 2025

https://www.ree.es/en/press-office/news/press-release/2025/06/red-electrica-presents-report-incident-28-april-and-proposes-recommendations

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» Grid Incident in Spain and Portugal on 28 April 2025

ICS Investigation Expert Panel
Factual Report

https://www.entsoe.eu/publications/blackout/28-april-2025-iberian-blackout/

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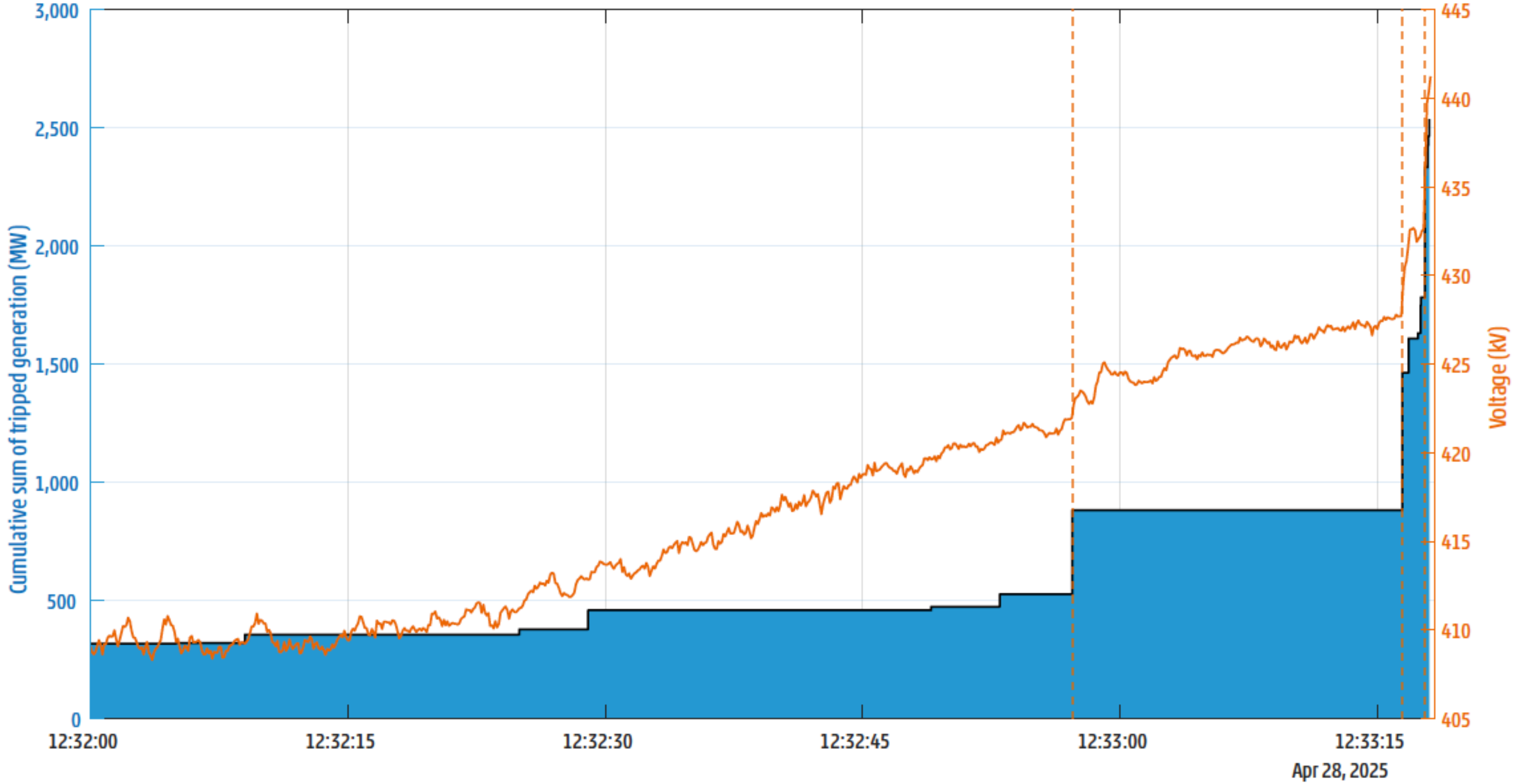
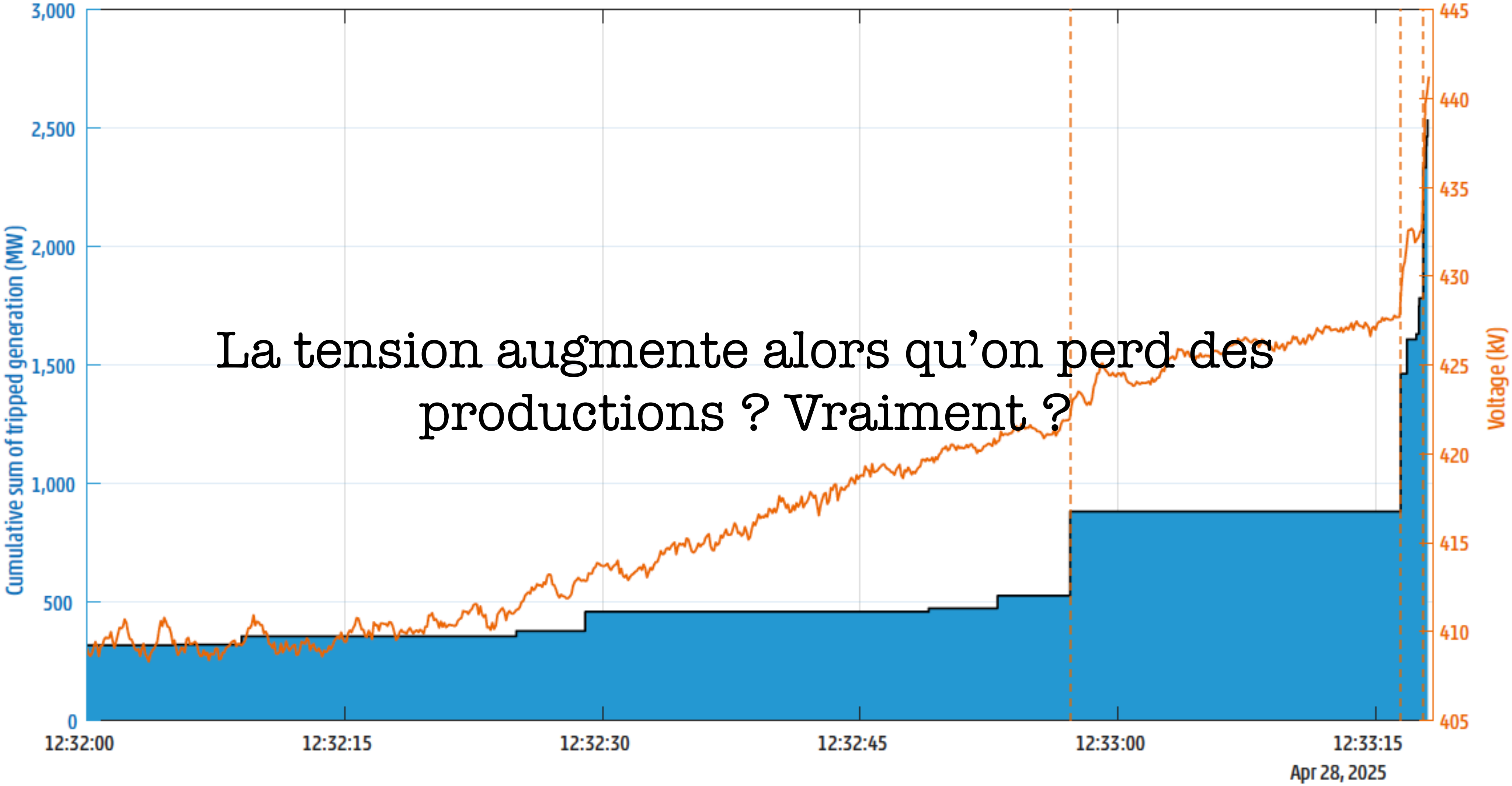
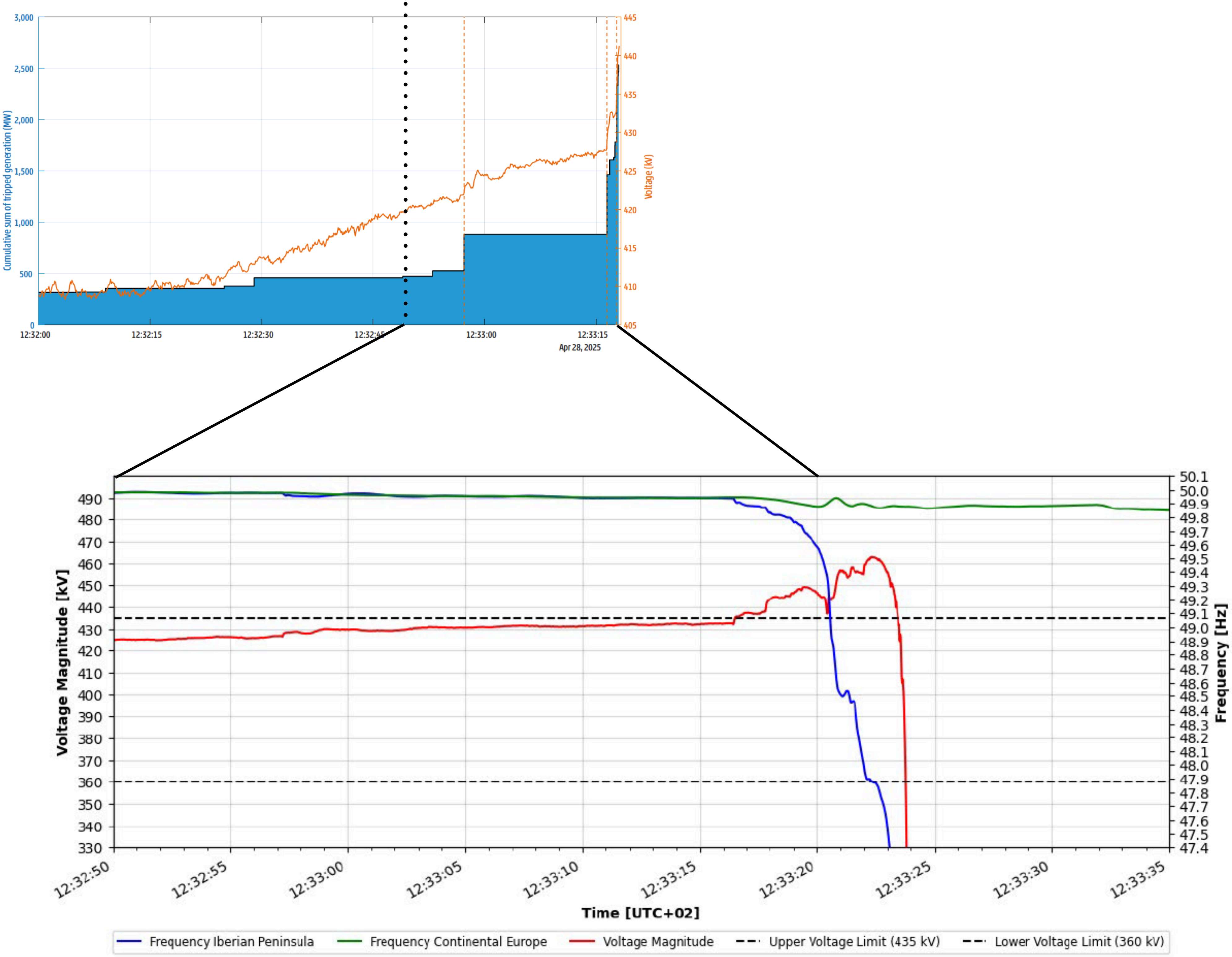


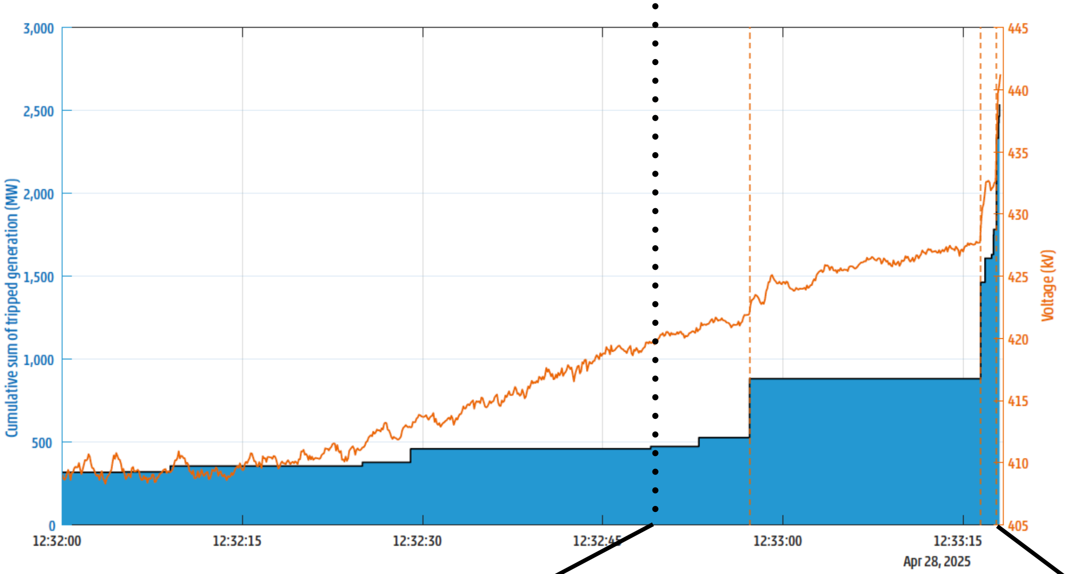
3,000
2,500
2,000
1,500
1,000
500
0
Cumulative sum of tripped generation (MW)
445
440
435
430
425
420
415
410
405
Voltage (kV)
12:32:00
12:32:15
12:32:30
12:32:45
12:33:00
12:33:15
Apr 28, 2025



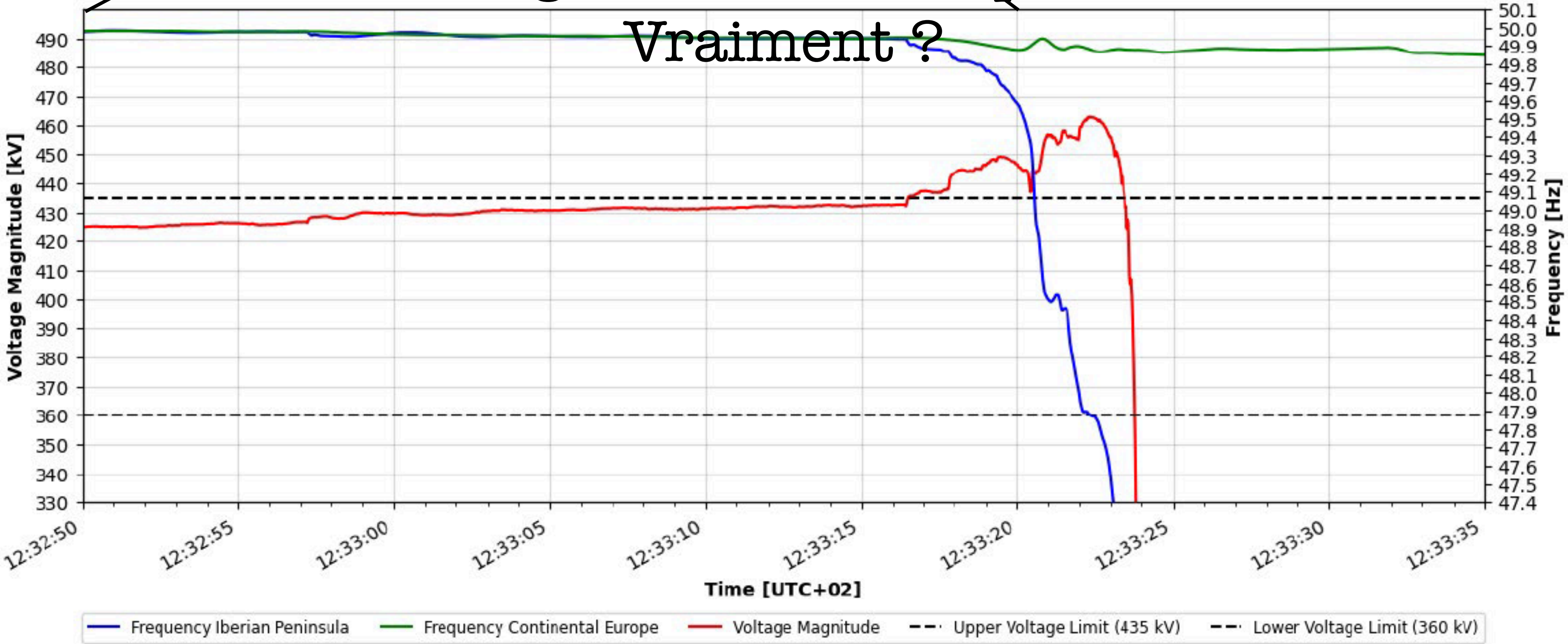
La tension augmente alors qu'on perd des productions ? Vraiment ?



Cumulative sum of tripped generation (MW)
Voltage (kV)
Apr 28, 2025
12:32:00
12:32:15
12:32:30
12:32:45
12:33:00
12:33:15
Voltage Magnitude [kV]
Frequency [Hz]
Time [UTC+02]
Frequency Iberian Peninsula
Frequency Continental Europe
Voltage Magnitude
Upper Voltage Limit (435 kV)
Lower Voltage Limit (360 kV)



La tension augmente et la fréquence baisse ? Vraiment ?



Don’t worry about things you can’t control.

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Worry about things you should but don’t control.

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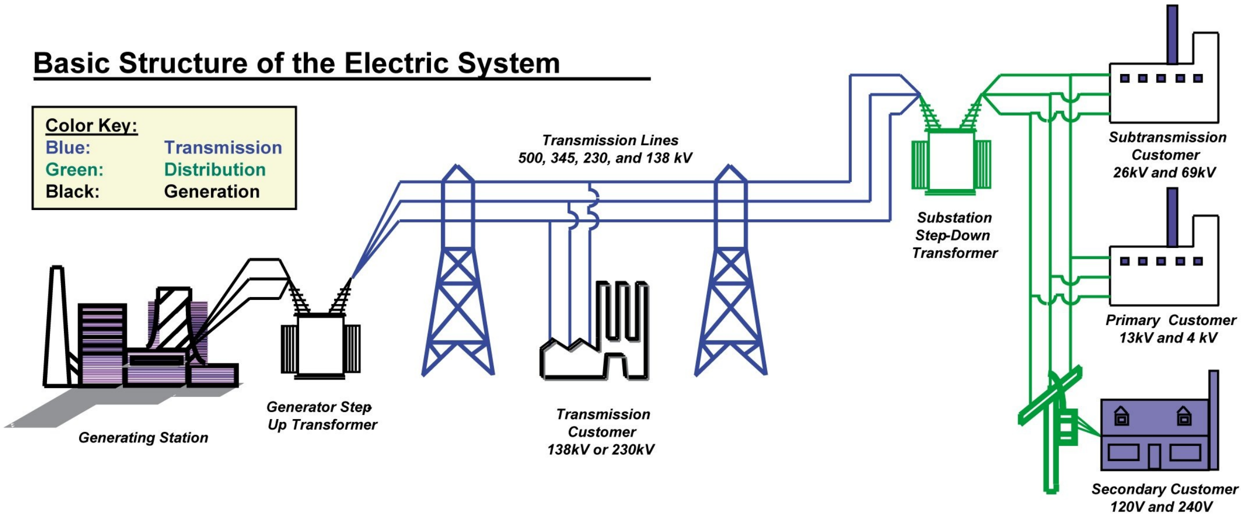
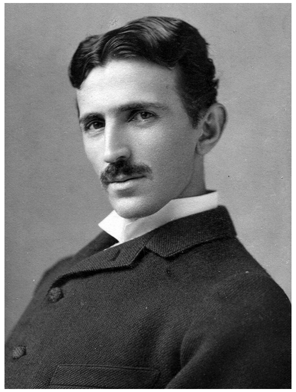
What are electric power systems ? (XXth century)





N Tesla 1856-1943

- AC electric current/voltages (minimize losses ~ high voltages, but then need transformers)

- AC ~ frequency coupled to power balance
- State determined by complex voltage

$$V_i(t) = |V_i(t)| \exp[i\theta_i(t)]$$

$$\theta_i(t) = (\omega_i + \omega_0)t + \theta_0$$

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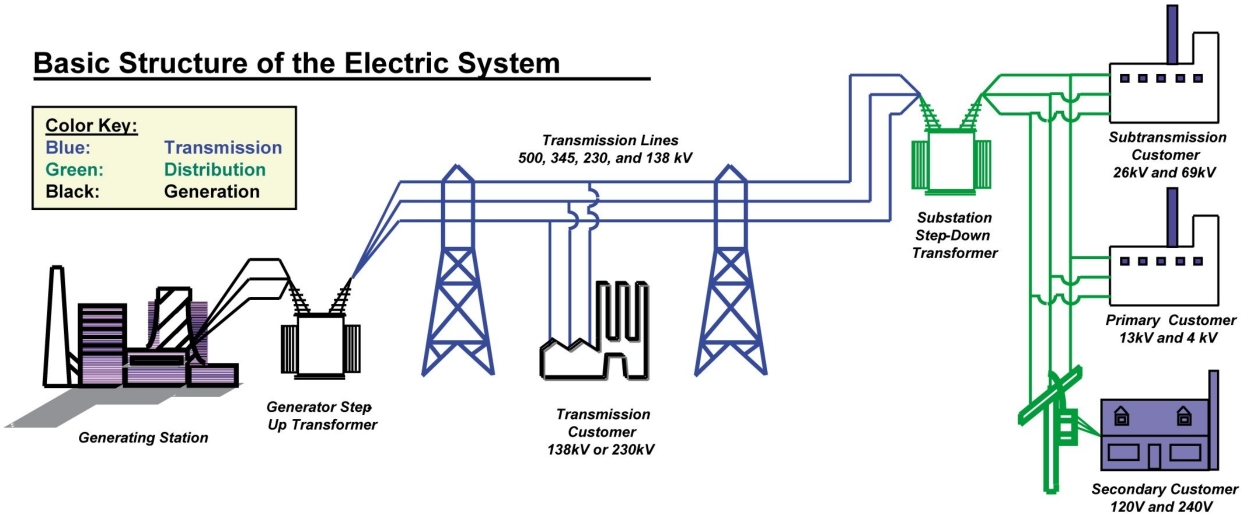

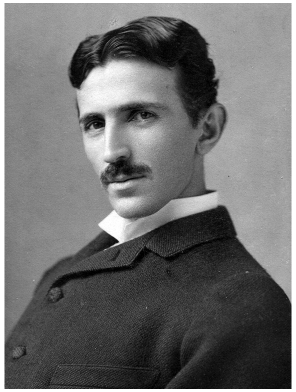

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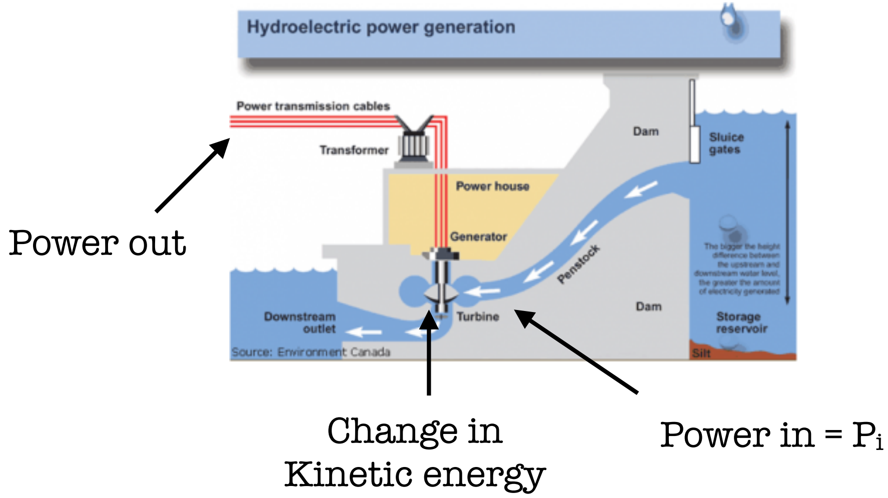

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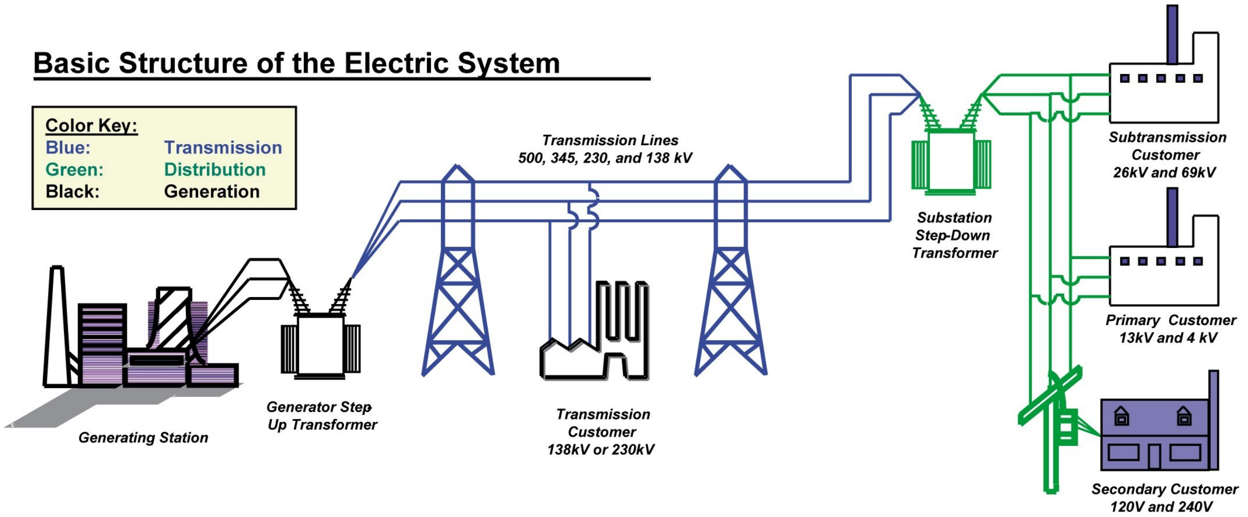

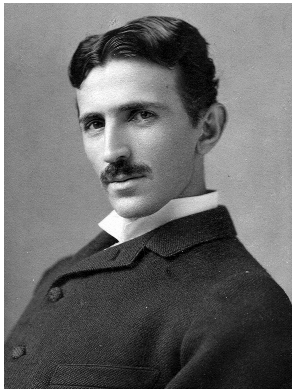

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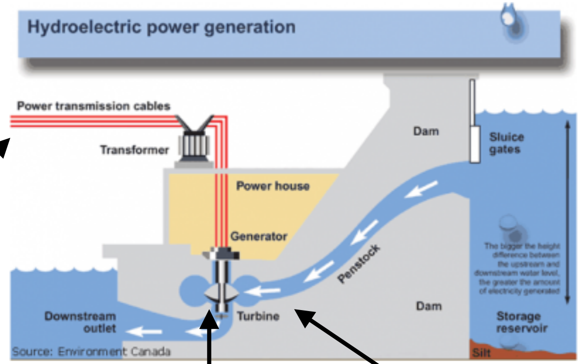

Power out

Change in Kinetic energy

Power in = P_i

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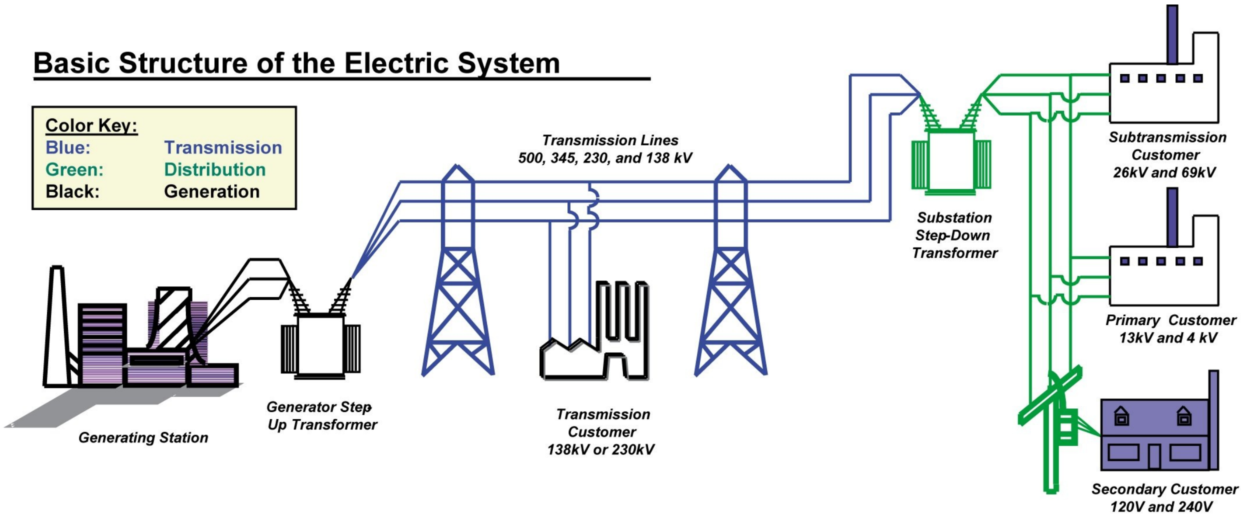

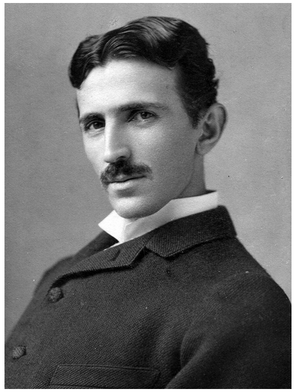

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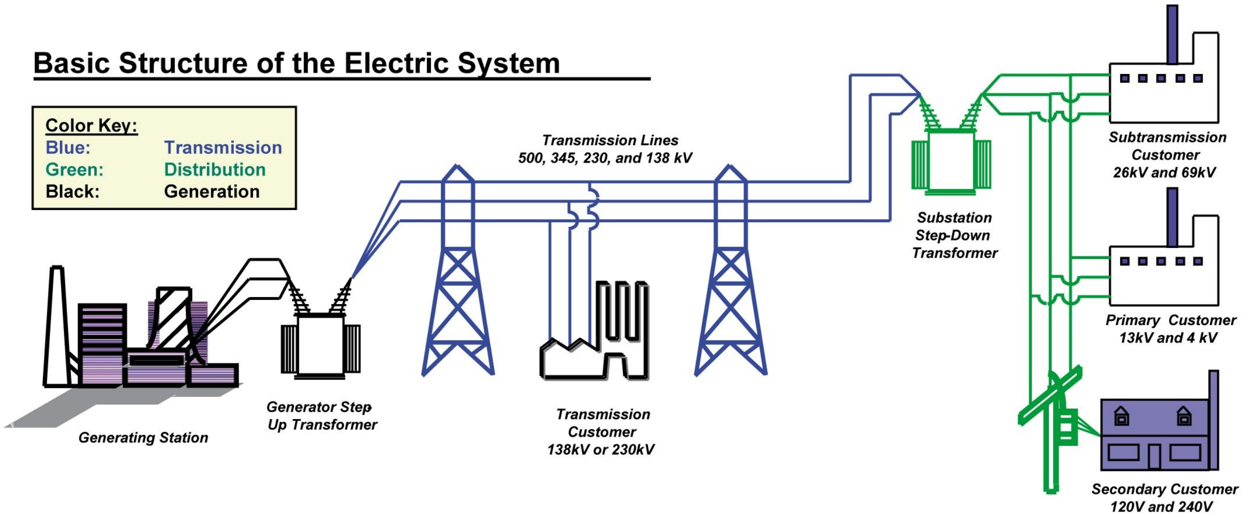

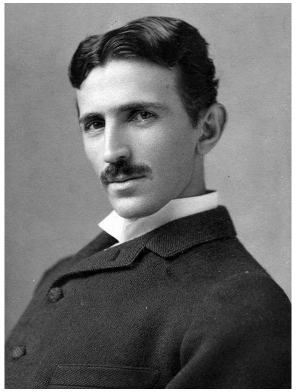

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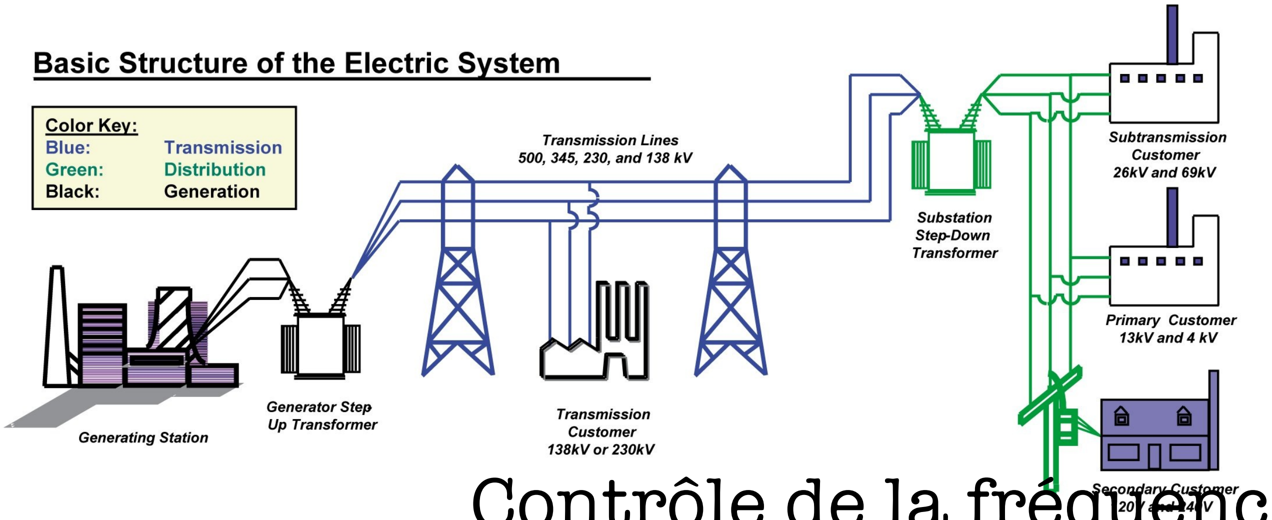

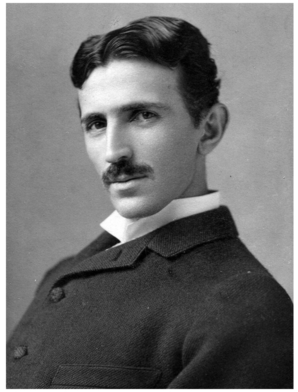

N Tesla 1856-1943

Contrôle de la fréquence :
augmenter / diminuer P

- AC electric current/voltages
  (minimize losses ~ high voltages,
  but then need transformers)

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Steady-state operation

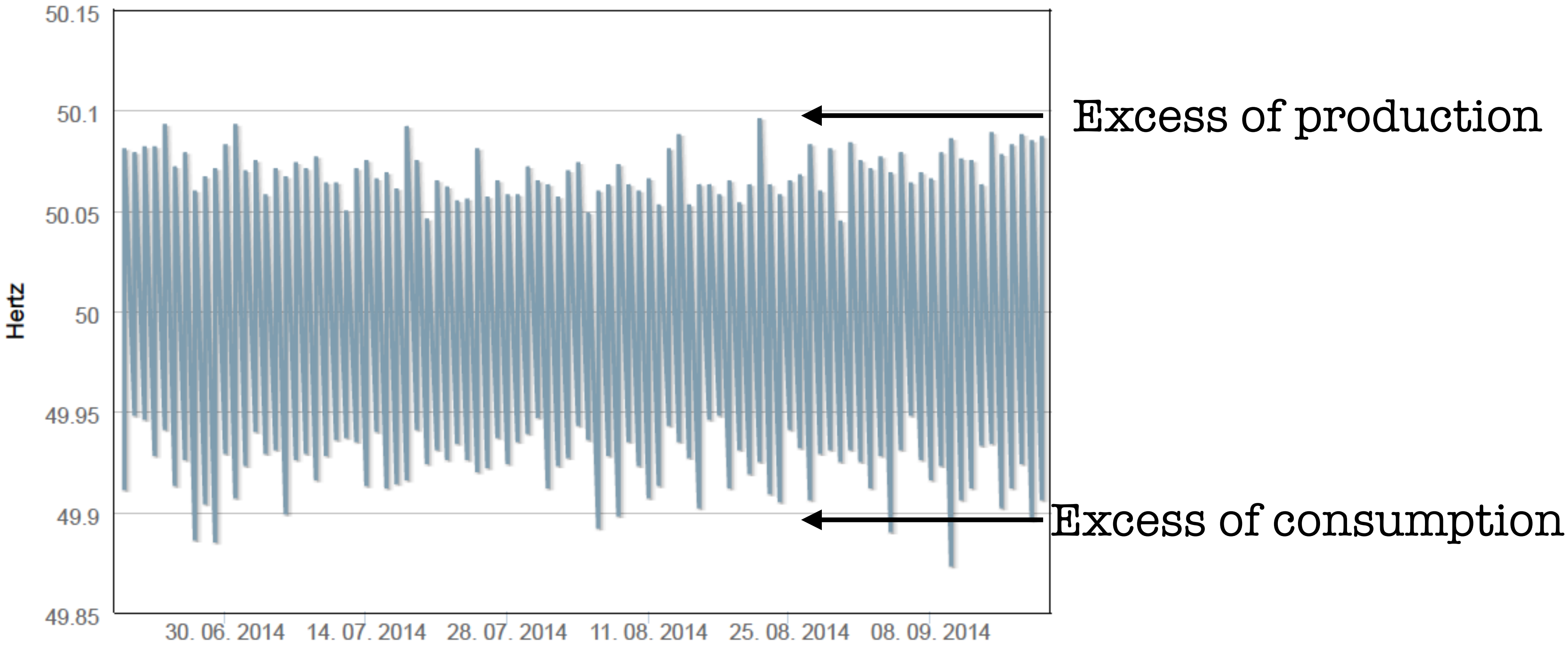
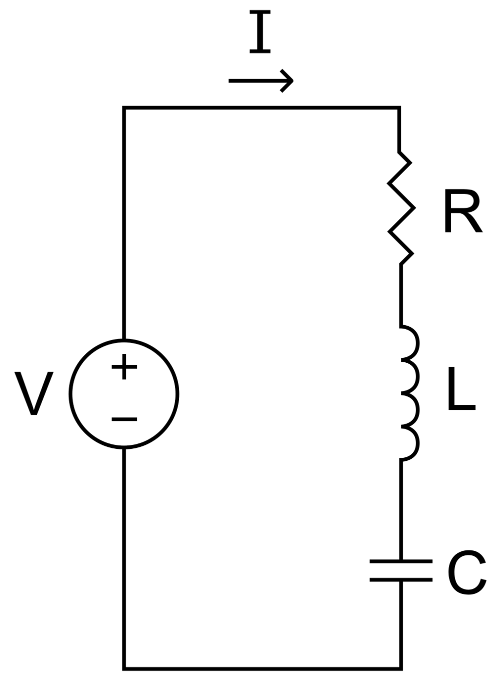


Figure from : www.swissgrid.ch

Electricity 101

RLC-circuit with voltage source

Derive equation for charge on capacitor
or current around circuit : *Kirchhoff voltage law*



Electricity 101

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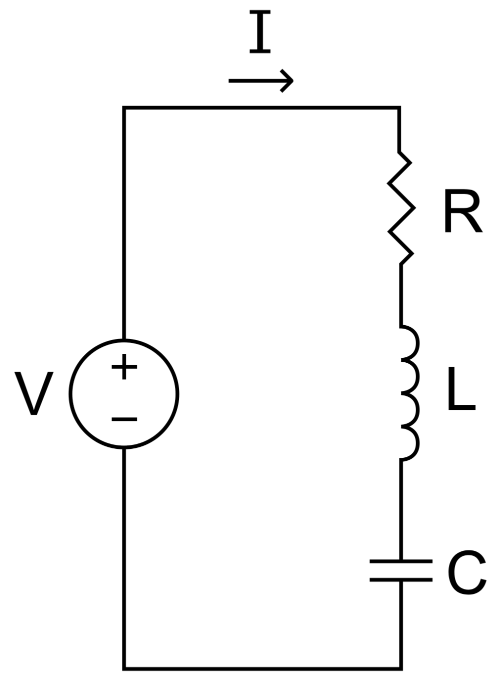
$$V_C + V_L + V_R = V$$



Electricity 101

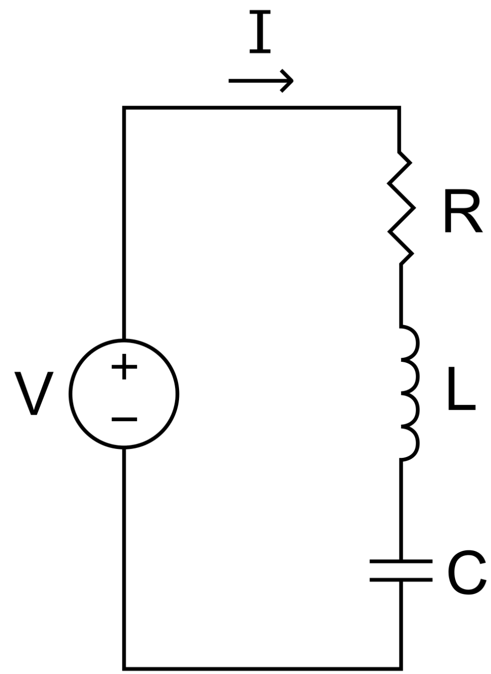
RLC-circuit with voltage source

Derive equation for charge on capacitor or current around circuit : ***Kirchhoff voltage law***

$$V_C + V_L + V_R = V$$

with (resistance, capacitor and inductance)

$$V_C = Q/C \qquad V_L = L\partial I/\partial t \qquad V_R = RI$$



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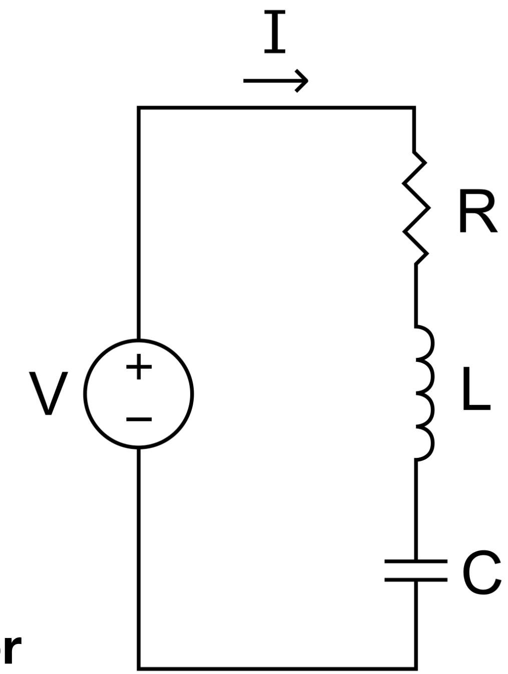
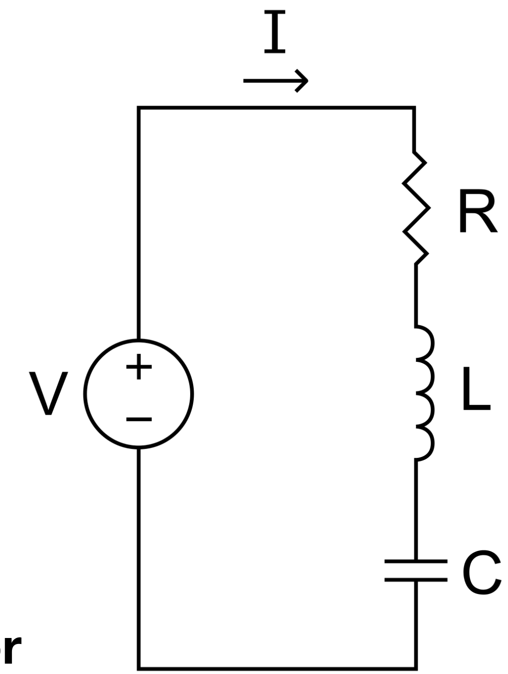


This gives a differential equation for a damped, driven oscillator

$$\boxed{\partial^2 I/\partial t^2 + (R/L)\partial I/\partial t + \omega_0^2 I = L^{-1}\partial V/\partial t} \qquad \omega_0 = 1/\sqrt{LC}$$

Electricity 101



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Solve with complex functions

$$V(t) = V_0\cos(\Omega t) \to V_0 e^{i\Omega t} \qquad I(t) = I_0 e^{i\Omega t}$$

$$I(t) = \frac{\Omega V_0/L}{\sqrt{(\omega_0^2 - \Omega^2)^2 + (R/L)^2\Omega^2}} e^{i(\Omega t - \varphi)}$$

Electricity 101

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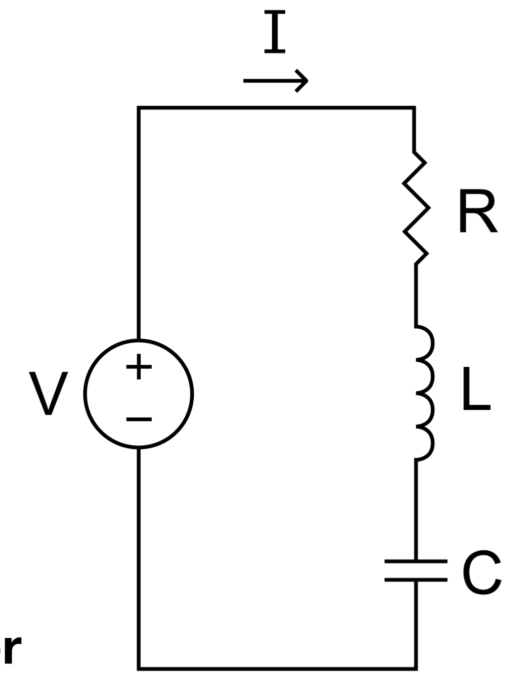

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-> phase difference between I(t) and V(t)

$$\varphi = \mathrm{atan}[(\Omega^2 - \omega_o^2)/((R/L)\Omega)]$$

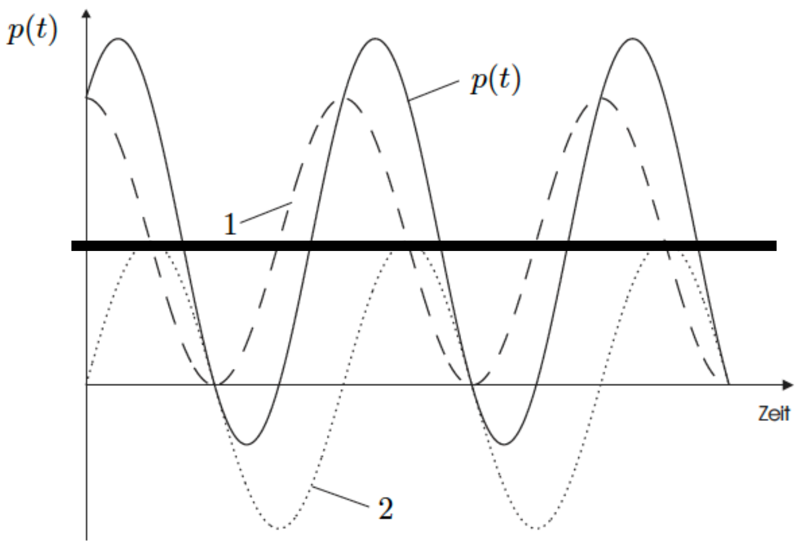
Electricity 101

Voltage and current

$$u(t) = \widehat{U}\cos(\omega t)$$
$$i(t) = \widehat{I}\cos(\omega t - \varphi)$$

Instantaneous power

$$p(t) = \frac{1}{2}\widehat{U}\widehat{I}\cos\varphi\Big(1+\cos(2\omega t)\Big) + \frac{1}{2}\widehat{U}\widehat{I}\sin\varphi\sin(2\omega t)$$



$$p(t) = \underbrace{\frac{1}{2}\widehat{U}\widehat{I}\cos\varphi\Big(1+\cos(2\omega t)\Big)}_{1} + \underbrace{\frac{1}{2}\widehat{U}\widehat{I}\sin\varphi\sin(2\omega t)}_{2}$$

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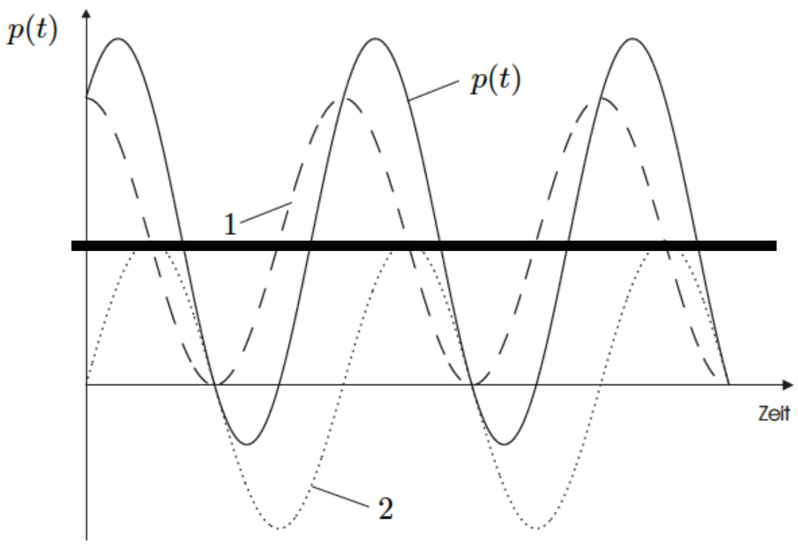
Time average = active power

$$P = \frac{1}{2}\widehat{U}\widehat{I}\cos\varphi = U I \cos\varphi$$



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Electricity 101

Voltage and current

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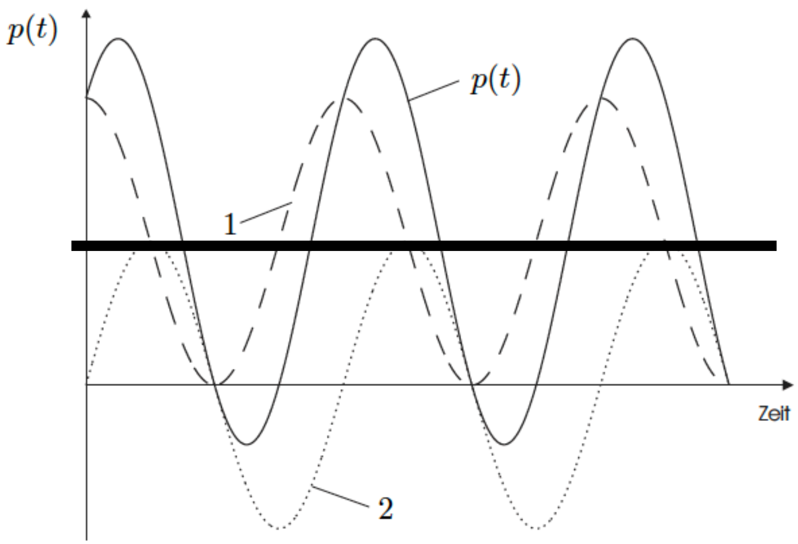
$$P=\frac{1}{2}\widehat{U}\widehat{I}\cos\varphi=UI\cos\varphi$$

Amplitude of 2nd term = reactive power

$$Q=\frac{1}{2}\widehat{U}\widehat{I}\sin\varphi=UI\sin\varphi$$



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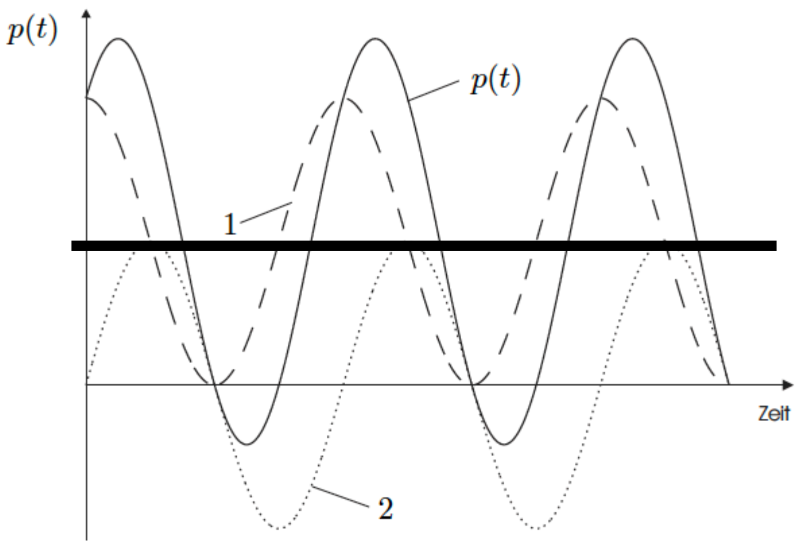
Amplitude of 2nd term = reactive power

$$Q = \frac{1}{2}\widehat{U}\widehat{I}\sin\varphi = UI\sin\varphi$$

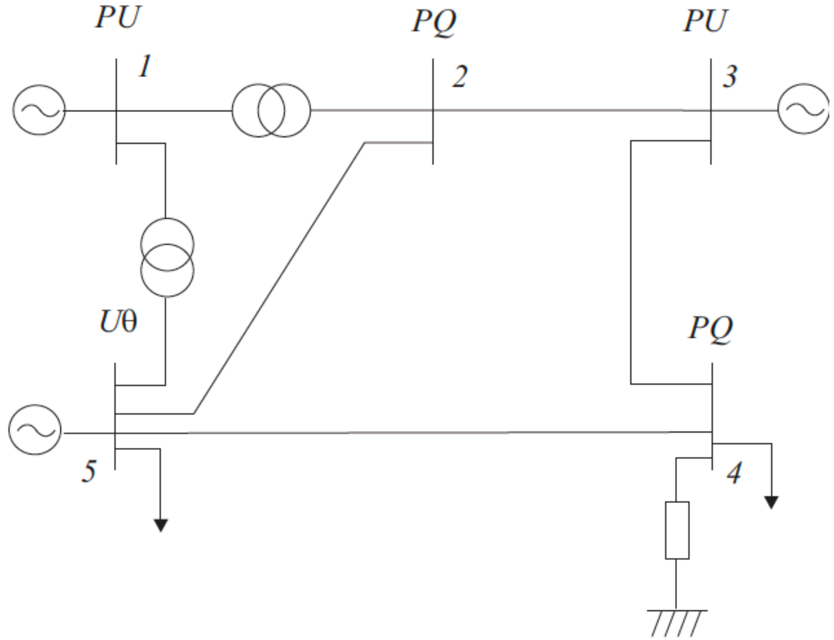


$$p(t) = \underbrace{\frac{1}{2}\widehat{U}\widehat{I}\cos\varphi\Big(1+\cos(2\omega t)\Big)}_{1} + \underbrace{\frac{1}{2}\widehat{U}\widehat{I}\sin\varphi\sin(2\omega t)}_{2}$$

Power flow equations (via AC Ohm's law)

$$P_i = \sum_j |V_i V_j| \left[G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right]$$

$$Q_i = \sum_j |V_i V_j| \left[G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right]$$



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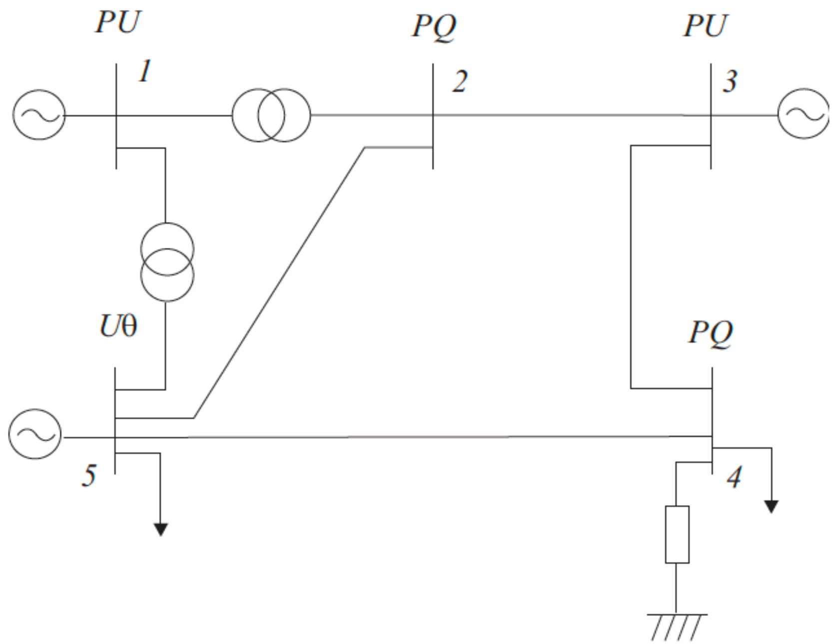
Linearize $\big\downarrow$ neglect G

$$P_i = \sum_j B_{ij} \, V_i \, V_j \, (\theta_i - \theta_j)$$

$$Q_i = \sum_j B_{ij} \, V_i \, (V_i - V_j)$$



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Linearize | neglect G

$$P_i = \sum_j B_{ij}\, V_i\, V_j\, (\theta_i - \theta_j)$$

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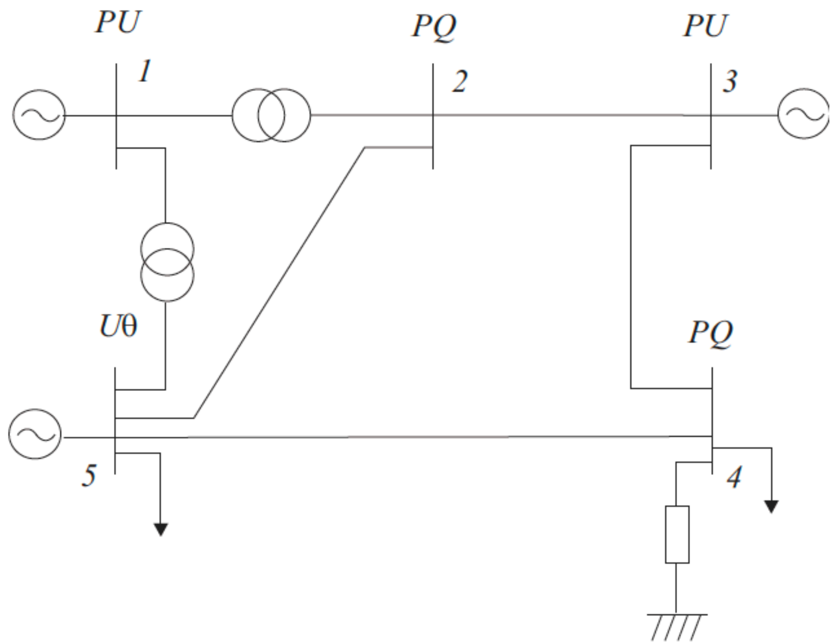

Contrôle de la tension:
Injecter Q>0 / Consommer Q<0

Qu’est-ce qui détermine la tension ?

Loi d’Ohm : U=R I

Les sources de courant sont à plus haute tension

Qu’est-ce qui détermine la tension ?

Loi d’Ohm : U=R I

Les sources de courant sont à plus haute tension

Situation avant l’événement :

A 12:30 le 28 avril, le réseau était approvisionné par 32 GW vs. 25 GW de demande.

Exportations de
- 2-2.5 GW vers le Portugal
- 0.8-1 GW vers la France
- 0.8 GW vers le Maroc

Le reste de l’excès était hydropompé - env. 3GW

Qu'est-ce qui détermine la tension ?

Loi d'Ohm : U=R I

Les sources de courant sont à plus haute tension

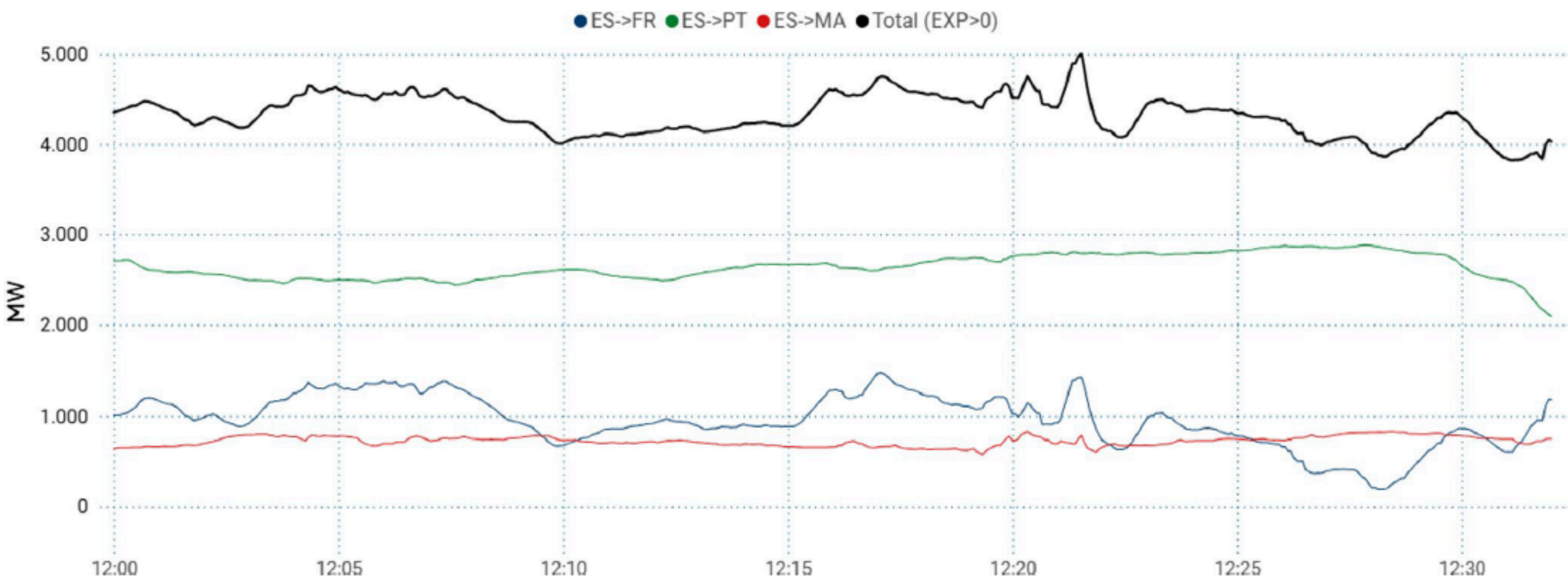

Figure 2-22: Physical flows through ES–FR, ES–PT, and ES–MA between 12:00 and 12:32 (source: RE SCADA)

Qu'est-ce qui détermine la tension ?

Loi d'Ohm : U=R I

Les sources de courant sont à plus haute tension

L'effet est d'autant plus grand que R est grand

Qu’est-ce qui détermine la tension ?

Loi d’Ohm : U=R I

Les sources de courant sont à plus haute tension

Régulation de tension

“les centrales consomment du réactif”

$$Q_i = \sum_j B_{ij} \, V_i \, (V_i - V_j)$$

Qu'est-ce qui détermine la tension ?

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Les sources de courant sont à plus haute tension

Régulation de tension

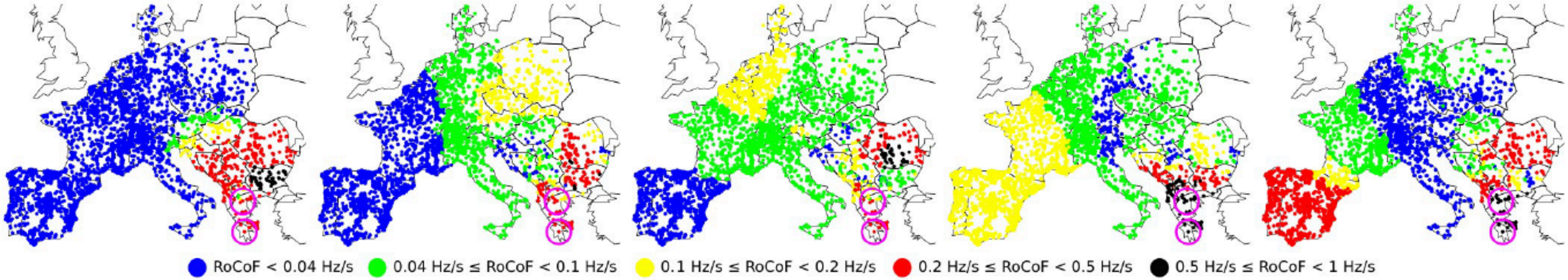
"les centrales consomment du réactif"

$$Q_i = \sum_j B_{ij} V_i (V_i - V_j)$$

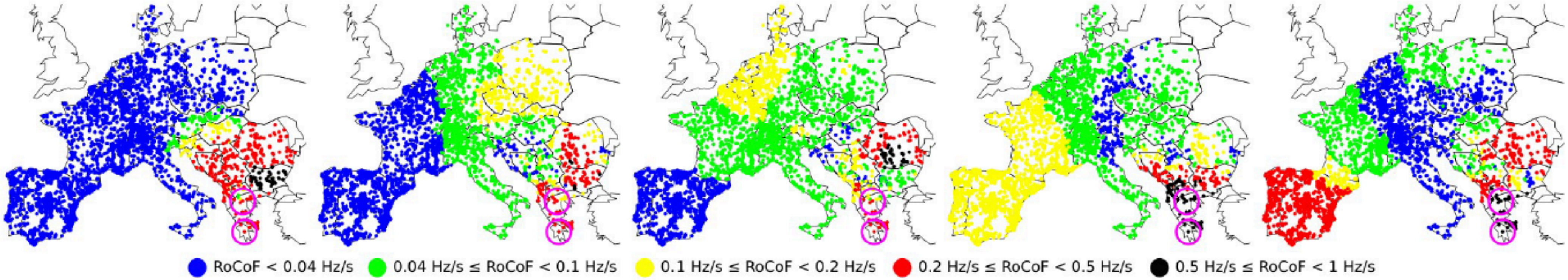
Effets capacitifs

Les lignes sous-chargées tendent à augmenter la tension

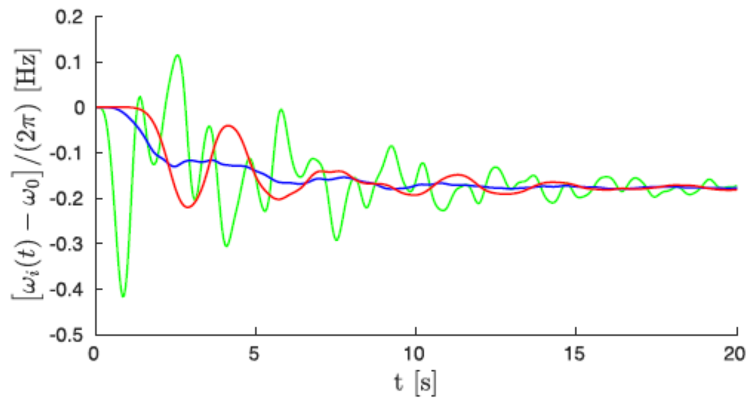
Oscillations interzones



Oscillations interzones

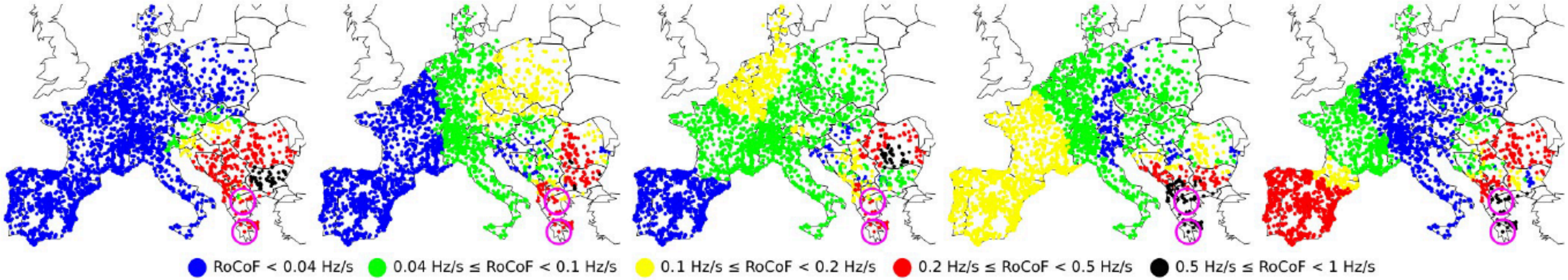


Des oscillations entre zones
Éloignées du résau apparaissent
périodiquement ~0.2Hz



Elles doivent être amorties
(Risque d'excursion)

Oscillations interzones



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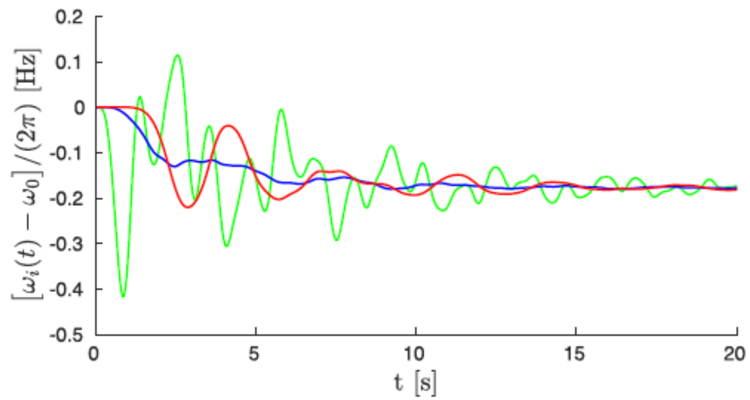
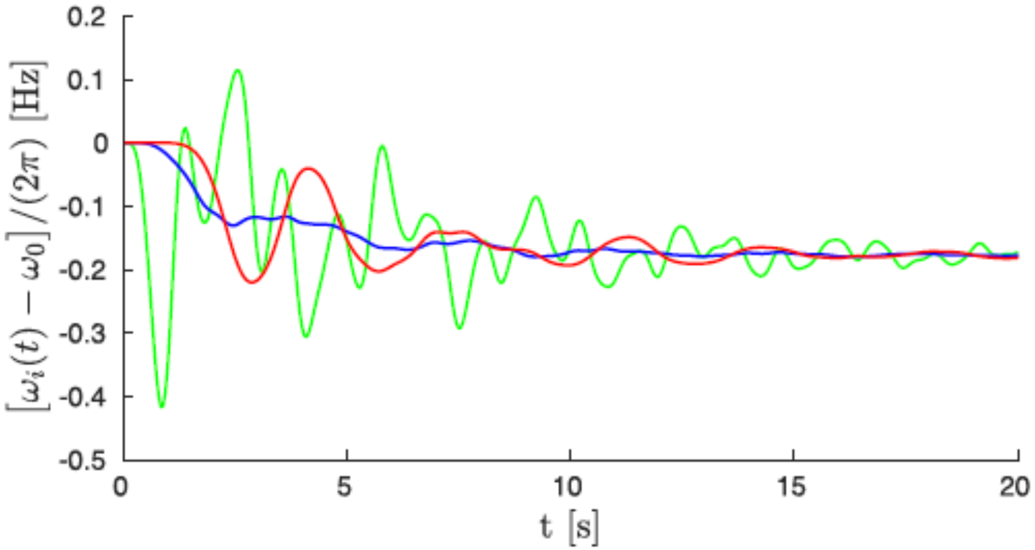


L. Pagnier & PJ, PlosOne 2019; J Fritzsch and PJ, IEEE Access 2022

Oscillations interzones



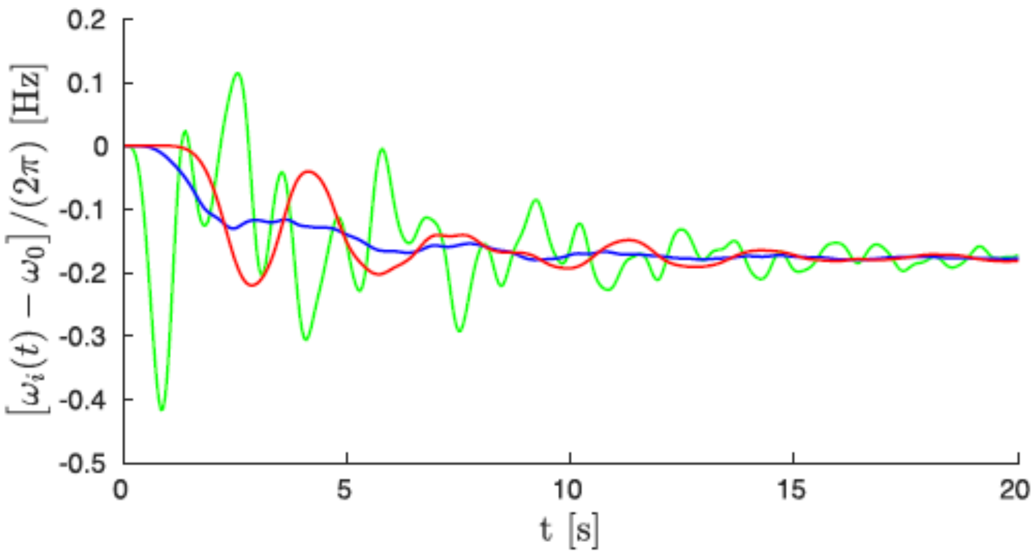
Comment les amortir ?

Augmenter le couplage entre les régions

Reconnecter des lignes

Réduire le flot entre les régions

Oscillations interzones



Comment les amortir ?

Augmenter le couplage entre les régions

Reconnecter des lignes

Réduire le flot entre les régions

=Augmenter le nombre de lignes sous-chargées...

L’événement (i)

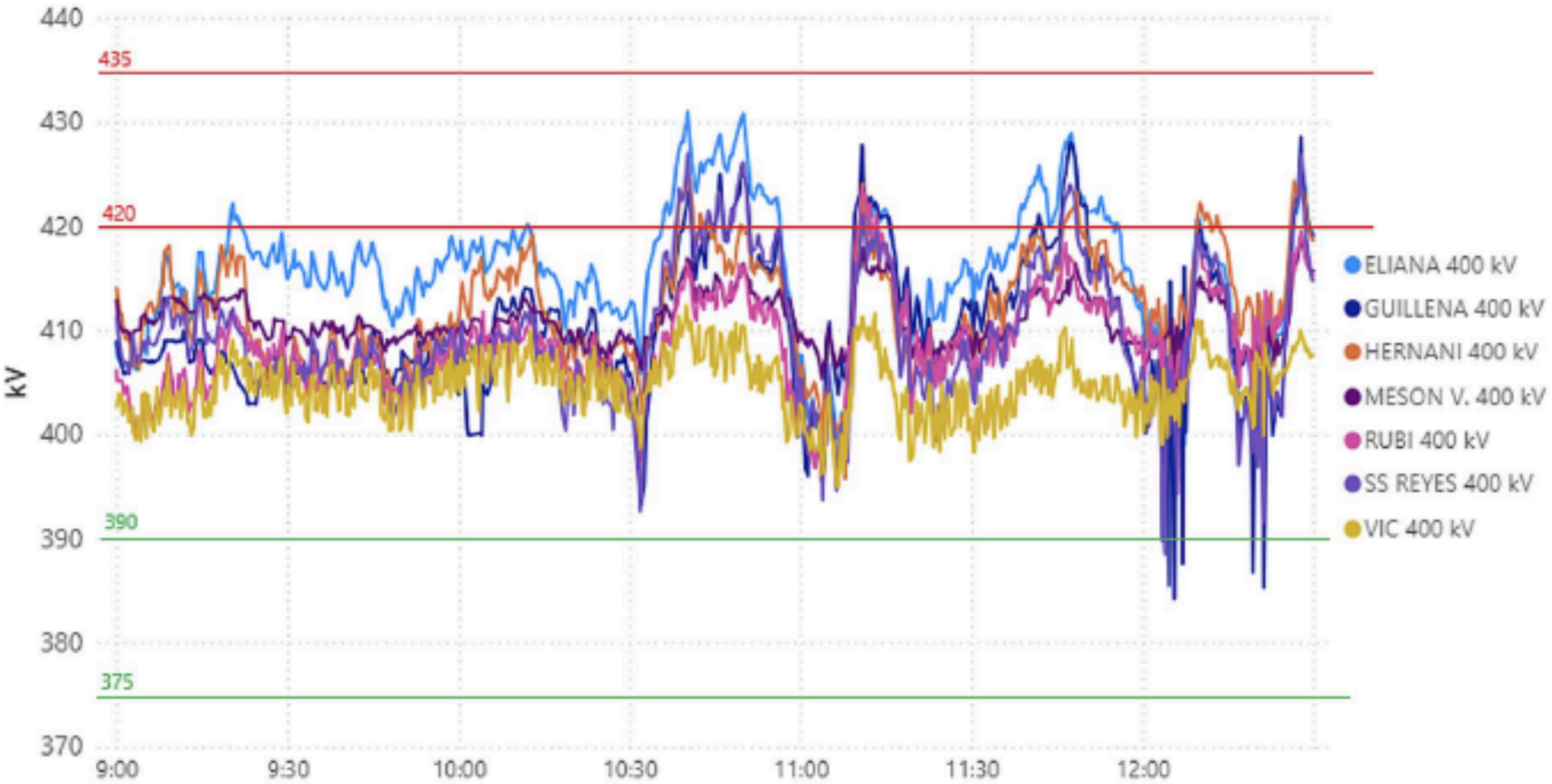


Figure 2-70: Voltage evolution at the main 400 kV transmission substations (pilot nodes) in Spain

L'événement (ii)

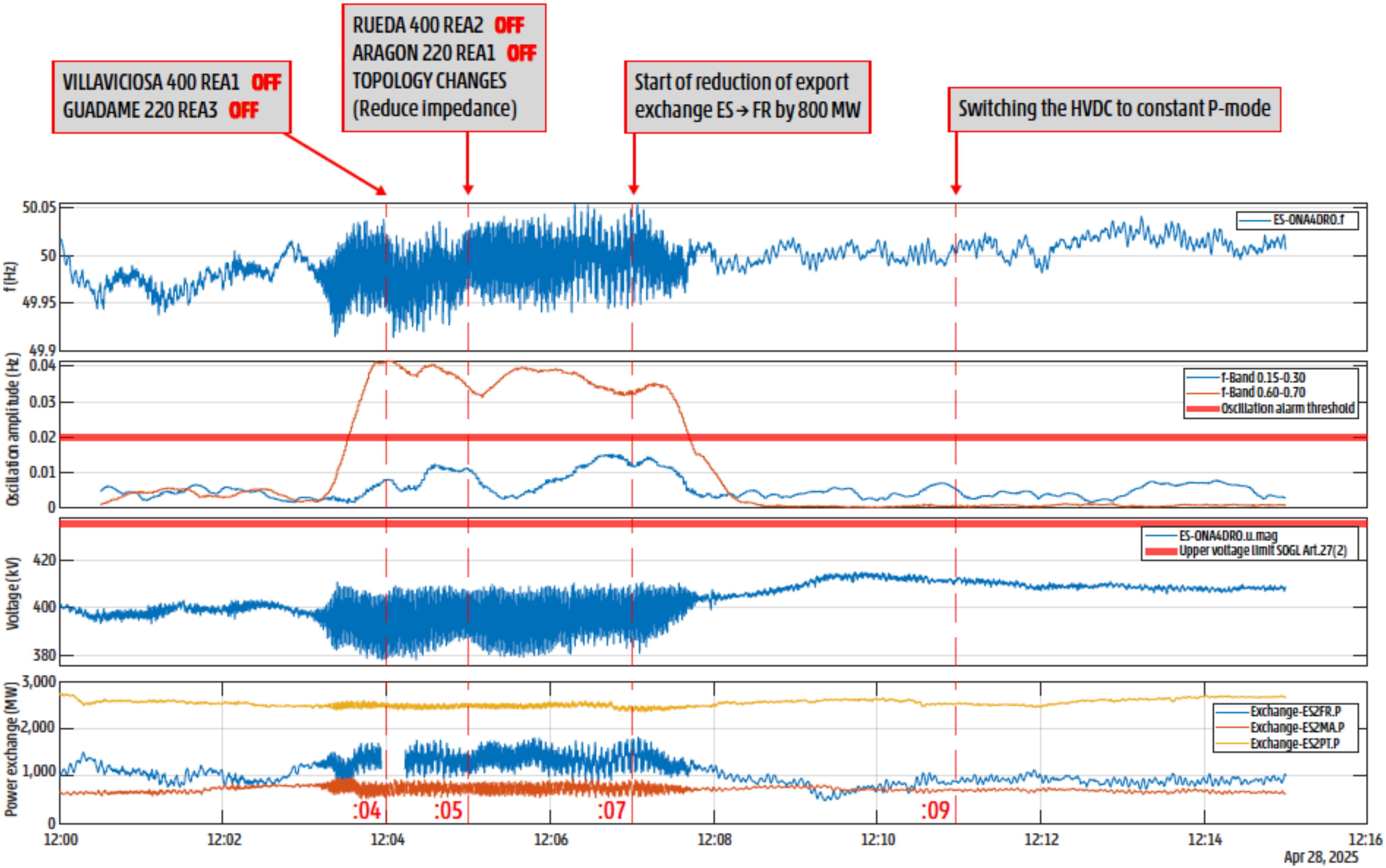


Figure 2-48: Characteristics data of the first oscillations (source: WAMS 100 ms sampling rate in the 6 kV Carmona (Spain) substation) and countermeasures applied

L'événement (iii)

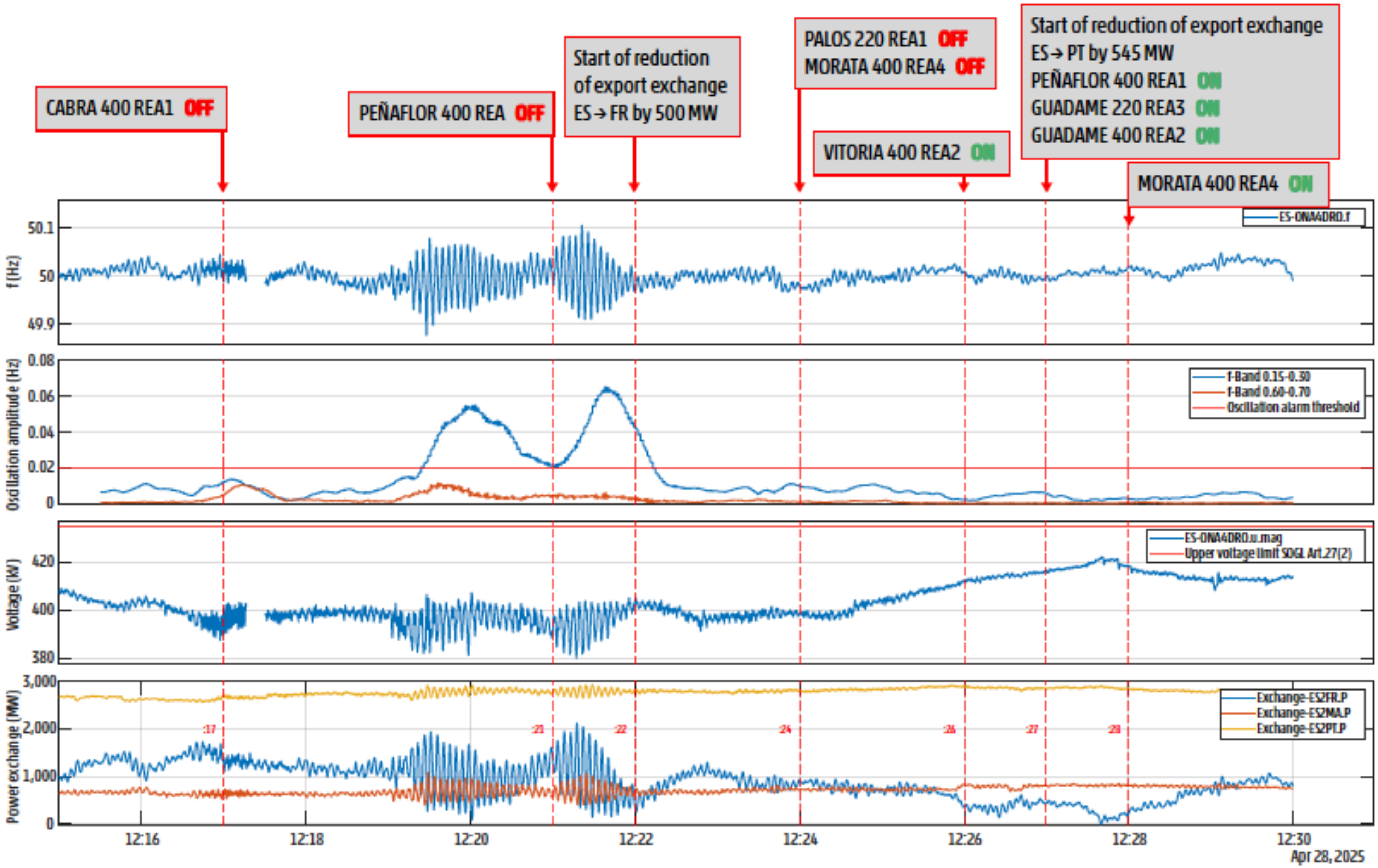


Figure 2-62: Characteristics data of the second oscillations and increasing voltage (source: WAMS 100 ms sampling rate at the 400 kV Carmona substation) and countermeasures

L’événement (iv)

Tension élevée - proche de la limite supérieure @435kV

L’événement (iv)

Tension élevée - proche de la limite supérieure @435kV

Oscillations à amortir

- -reconnection de lignes 400kV
- -réduction des flots vers la France
- =lignes sous-chargées
- =augmentation de la tension...

L'événement (iv)

Tension élevée - proche de la limite supérieure @435kV

Oscillations à amortir

-reconnection de lignes 400kV

-réduction des flots vers la France

=lignes sous-chargées

=augmentation de la tension...

Pas assez de ressources de contrôle-tension

L’événement (iv)

Tension élevée - proche de la limite supérieure @435kV

Oscillations à amortir

- -reconnection de lignes 400kV
- -réduction des flots vers la France
- =lignes sous-chargées
- =augmentation de la tension…

Pas assez de ressources de contrôle-tension

Cascade:

Série de coupure de production de centrales qui participaient au contrôle-tension ($Q<0$)

L’événement (iv)

Tension élevée - proche de la limite supérieure @435kV

Oscillations à amortir

-reconnection de lignes 400kV
-réduction des flots vers la France
=lignes sous-chargées
=augmentation de la tension…

Pas assez de ressources de contrôle-tension

Cascade:

Série de coupure de production de centrales qui participaient au contrôle-tension ($Q<0$)

La tension continue d’augmenter, d’autres centrales tombent…

L’événement (iv)

Les conclusion finales n’ont pas encore été publiées par ENTSO-E.

Mais il semble clair que

-le problème provient d’une interférence entre le contrôle d’oscillations de fréquence et le contrôle de tension

-qu’il n’y avait pas assez de contrôle-tension / qu’on n’y a pas assez prêté attention

-les délestages auraient également coupé de la consommation de réactif…

Thank you for your attention!

Questions ?