Le réseau de transport d'électricité

Large grid EMT modeling
Challenges and perspectives from a TSO point of view

March 24th, 2026

SEBASTIEN DENNETIERE

EMT Webinar series
Organized by Oak Ridge National Laboratory (ORNL) in collaboration with North American Electric Reliability Corporation (NERC)

Presenter Bio

Sébastien DENNETIERE

Education

- Graduated from Supélec (2002) in France
- M.Sc., École Polytechnique de Montréal (2003) in Canada
- Ph.D., École Polytechnique de Montréal (2017) in Canada

Professional Experience

- Hydro-Québec (2002–2007): R&D on Electromagnetic Transient simulation
- EDF (2007–2009): EMT analysis and modeling
- RTE (2010–present): Technical expert in power system simulation & HVDC
- RTE international (2018–present) : Consultant on HVDC and IBR integration projects worldwide

Areas of Expertise

- Electromagnetic transients (EMT) simulation
- HVDC systems design review and integration study
- Inverter-based resources integration
- Power system modeling & simulation

Professional Involvement

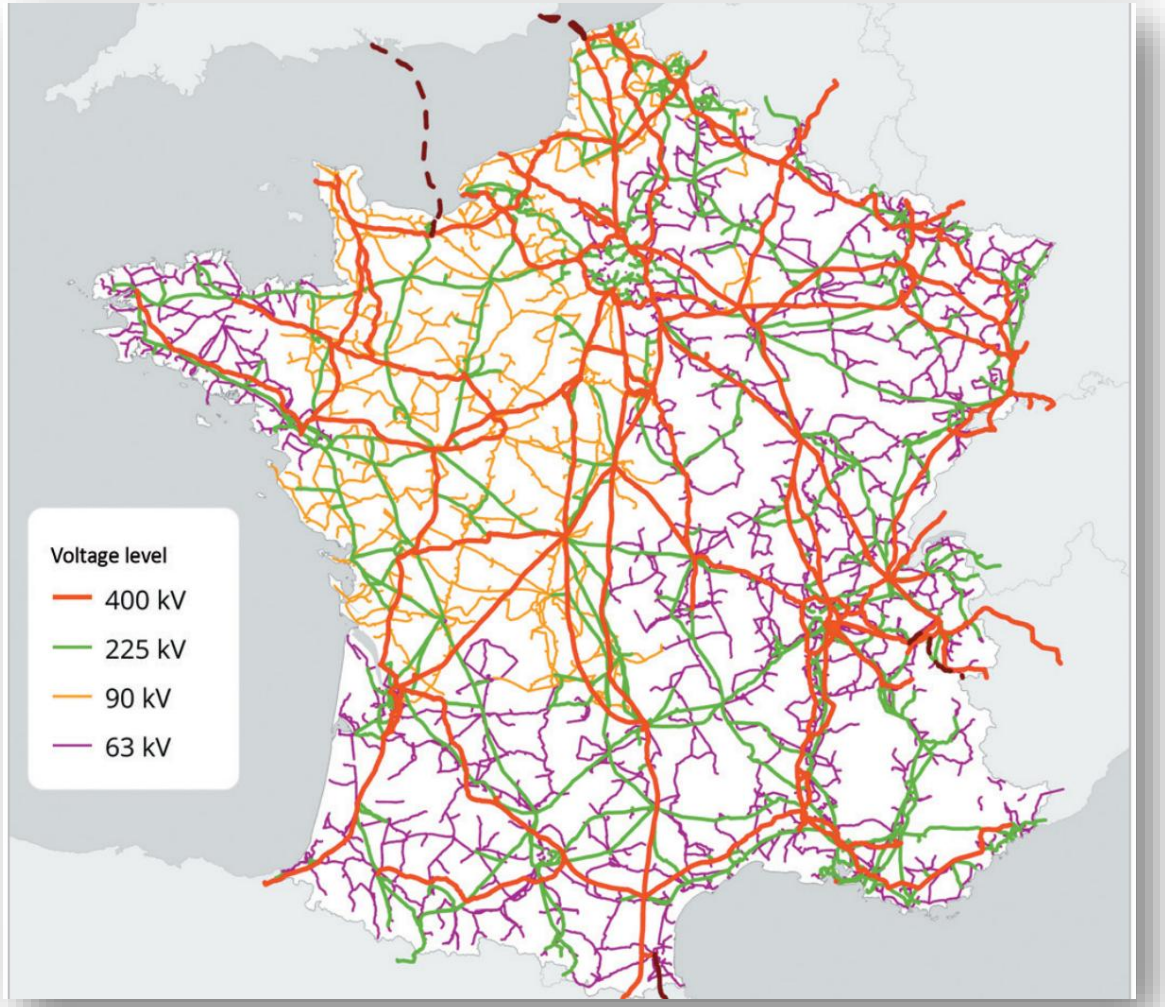
- Active member of IEEE, CIGRE, IEC Working Groups
- Former convener of CIGRE WG B4-70 – “Guide for Electromagnetic Transient Studies Involving VSC Converters” - TB 832
- Special reporter of the B4 Study Committee during the CIGRE 2026 session

RTE introduction

National System Operator and Transmission Owner for mainland France.

RTE introduction

- National System Operator (SO) and Transmission Owner (TO) for mainland France.
- Operates the high voltage (≥ 50 kV) and extra-high voltage (≥ 220 kV) transmission grid.
- Manages 37 interconnections with neighboring power systems.
- Connects offshore generation facilities: 3 in operation, 9 under construction or development.
- A regulated public company mandated by law to conduct long-term power system planning.



105,817 km
of power lines, the biggest grid in Europe

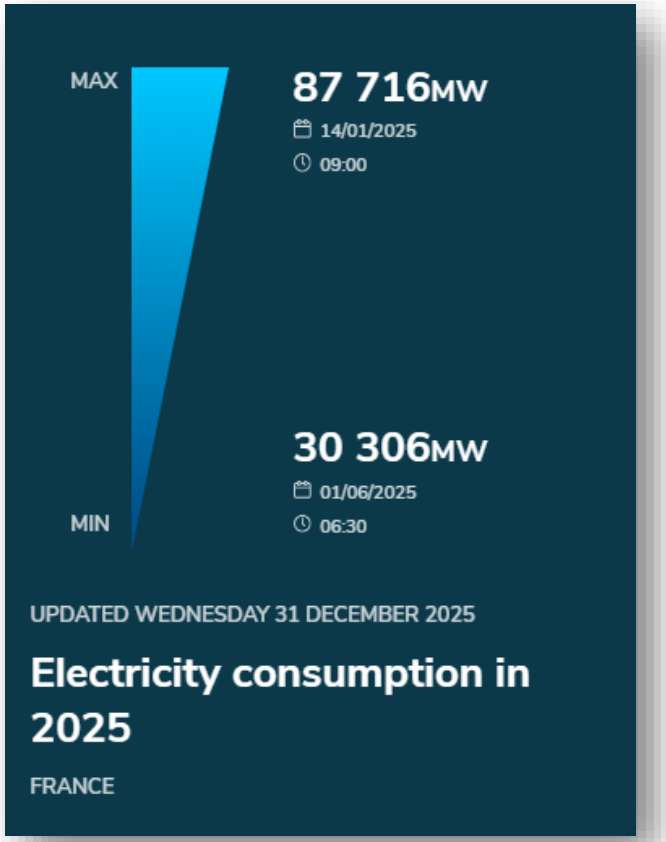
99.9995 %
power supply continuity

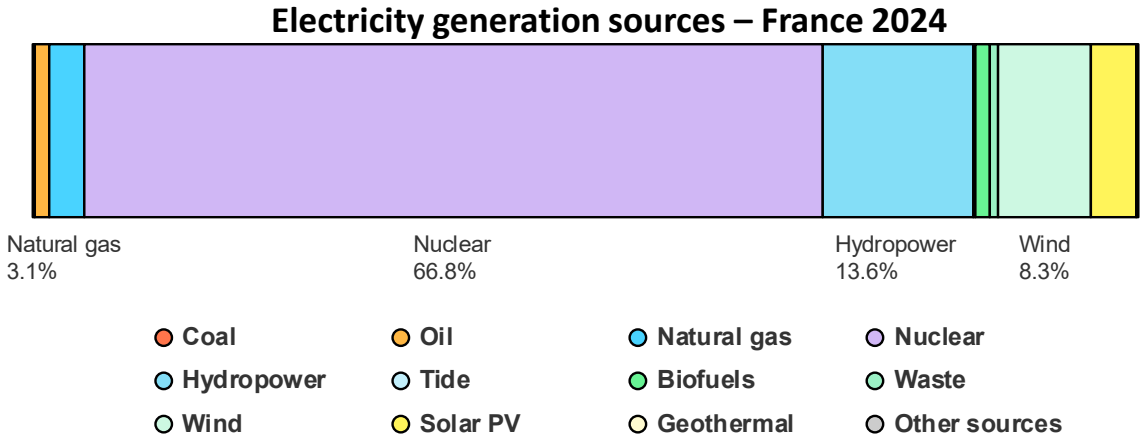
10,781
employees including around 540 apprenticeships

6,658 M€
of revenue in 2025

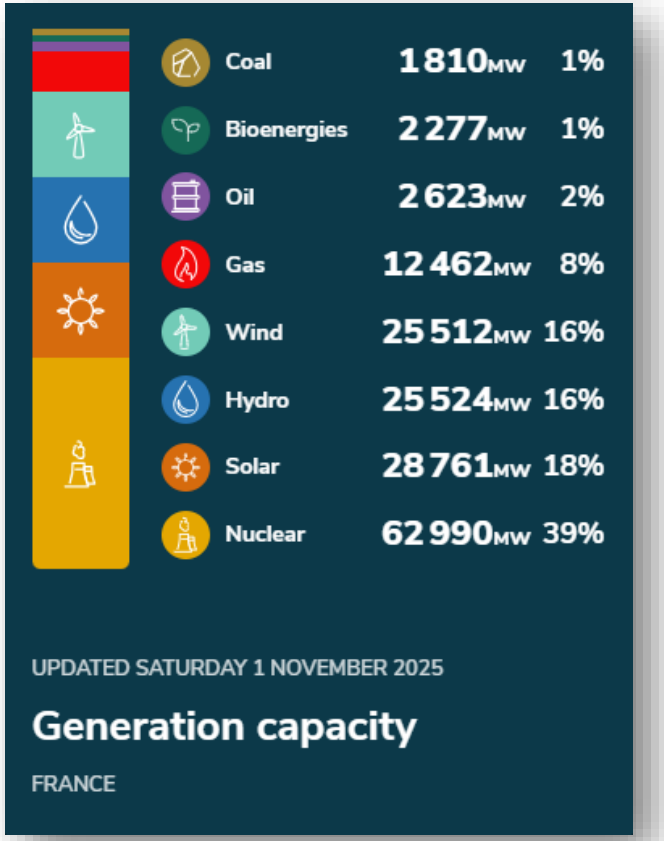
40 M€
worth of investment committed to R&D

RTE introduction



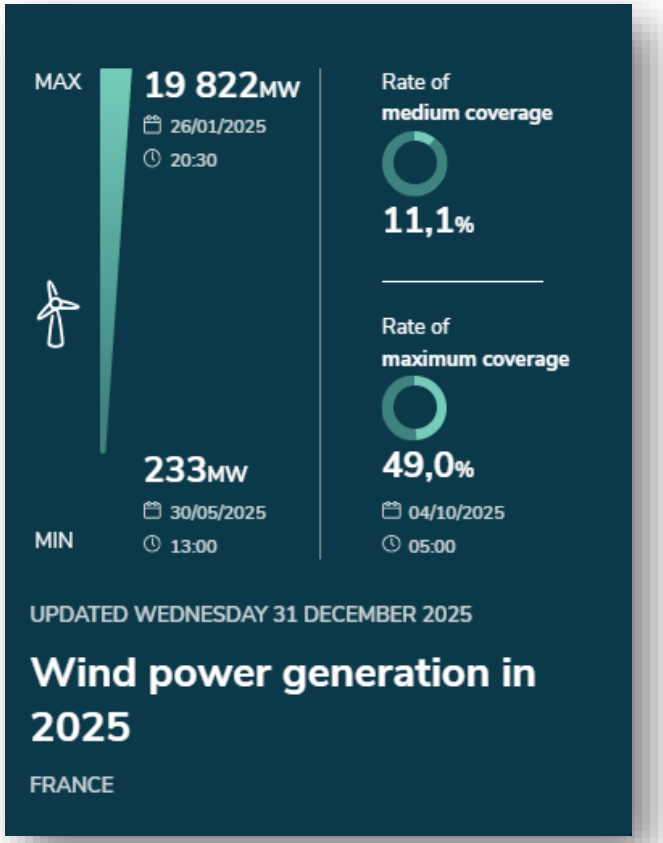


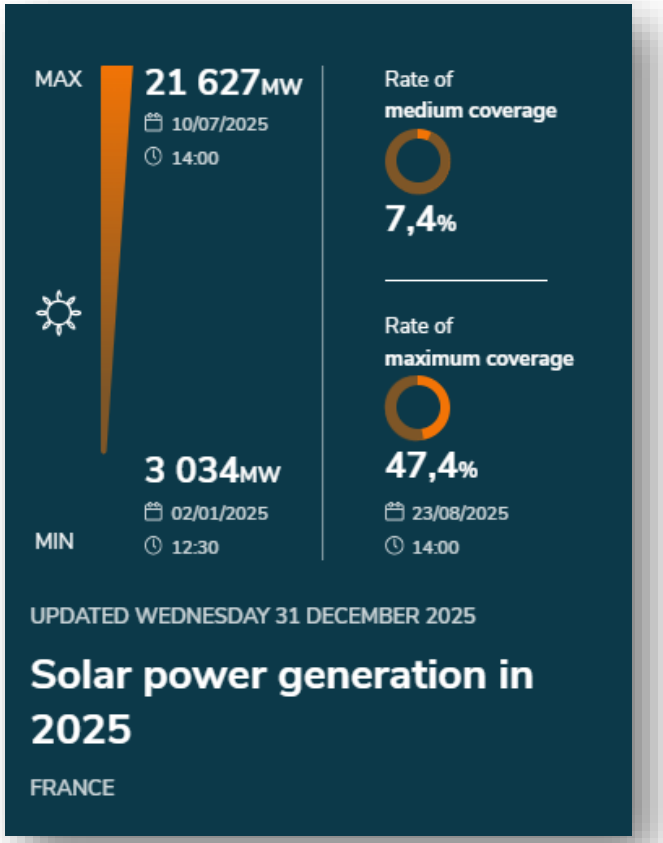
Source: International Energy Agency. Licence: CC BY 4.0

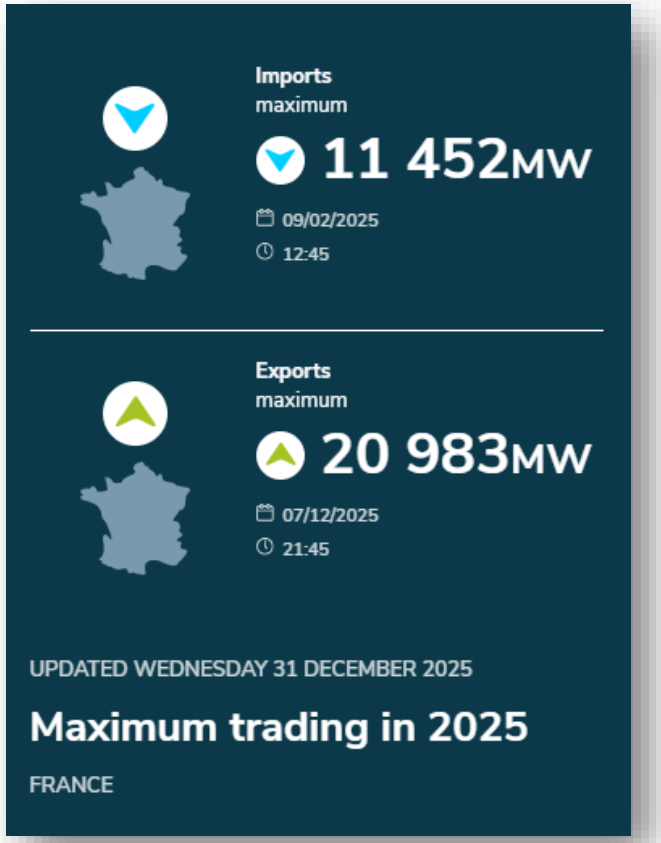


Source: https://www.rte-france.com/en/data-publications/eco2mix/key-figures

RTE introduction

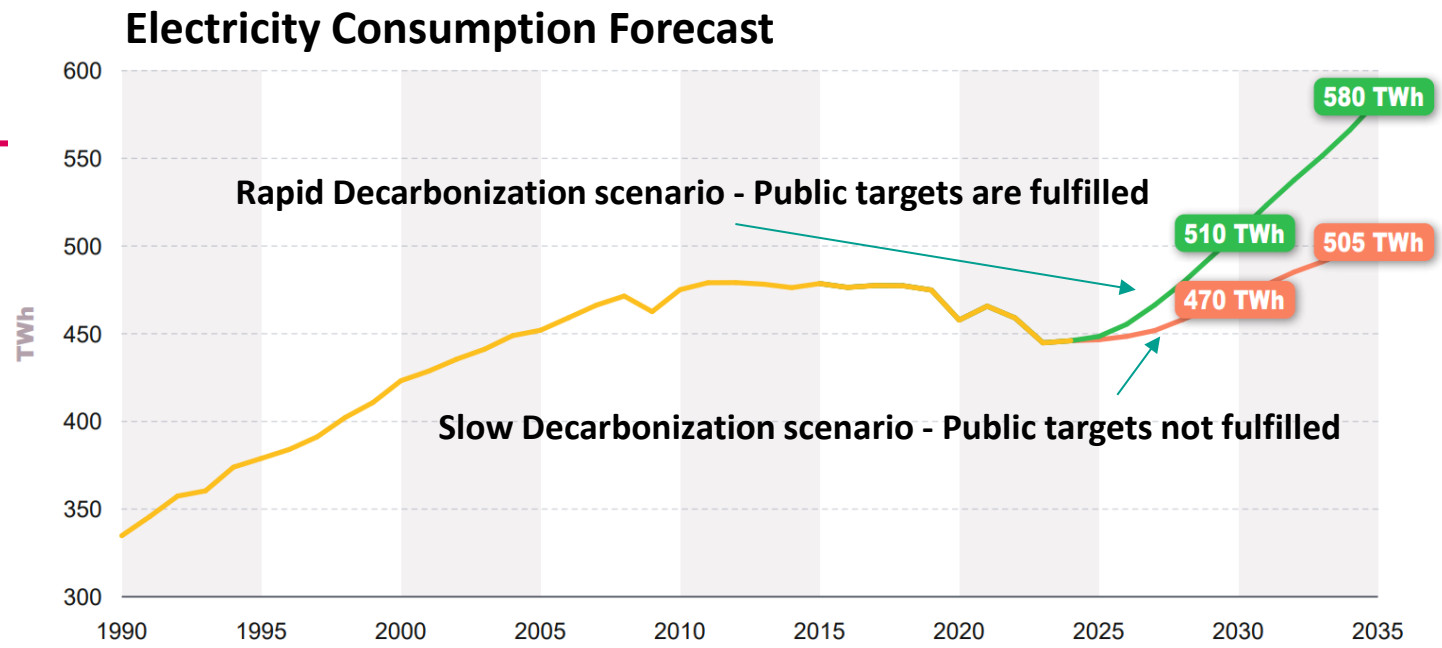






Source: https://www.rte-france.com/en/data-publications/eco2mix/key-figures

RTE introduction

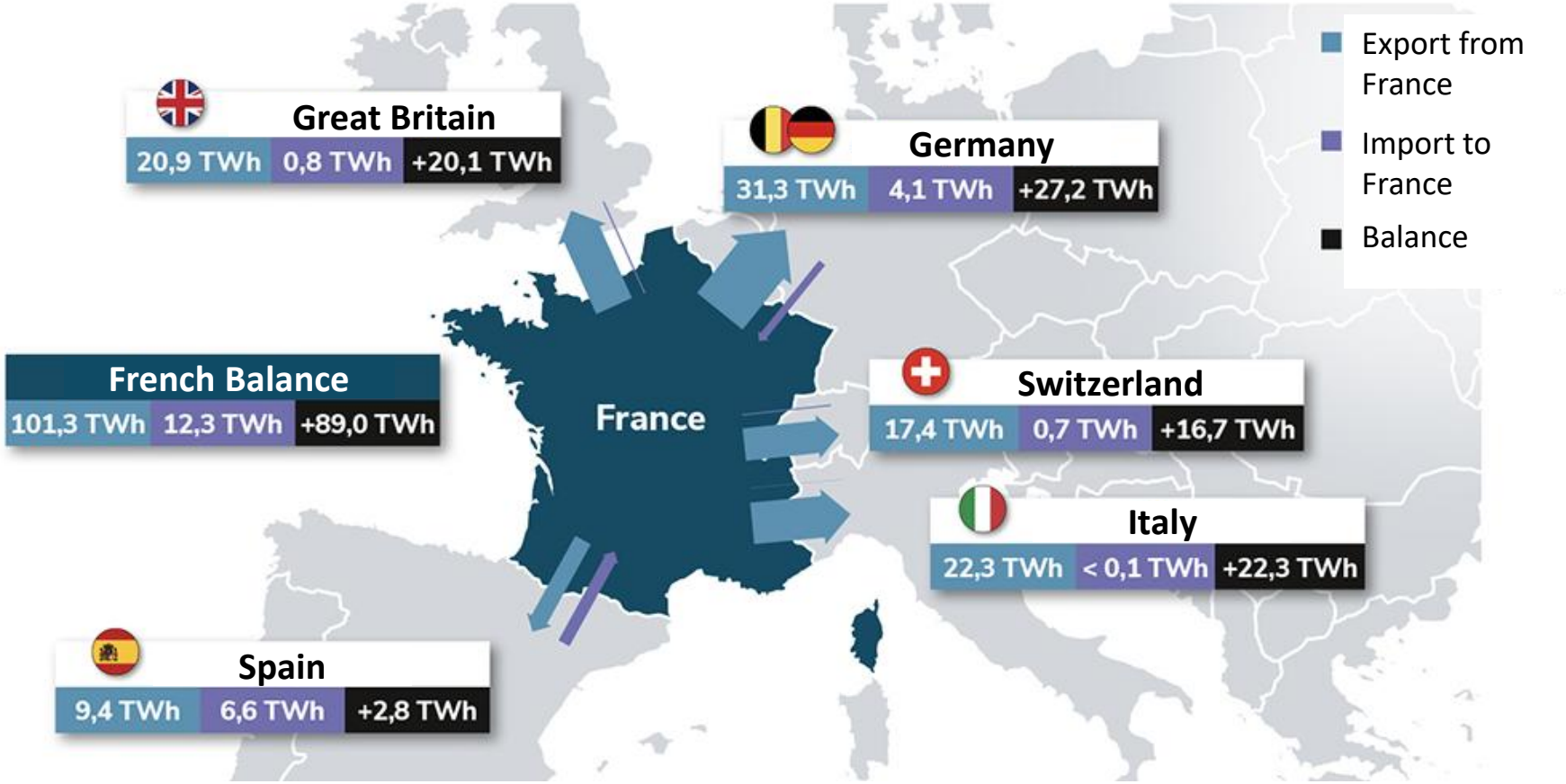


Generation Capacity

	2025	2035	2040
	54 GW	+ 46 GW	+ 89 GW
	1.5 GW	+ 18.5 GW	26 GW
	62 GW	+ 9.6 GW	69.5 GW
Low Scenario			+ 60 GW / 18 GW / 63 GW

Interconnections supporting an integrated European power system

400+ cross-border interconnections link nearly 600 million Europeans, strengthening security of supply.
Enable **competitive electricity markets** and foster the **integration of renewable energy**.
VSC HVDC technology is a key solution for interconnection



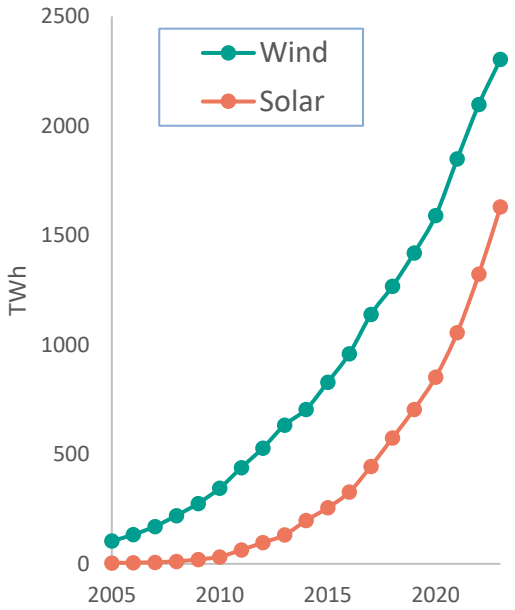
Electricity trade between France and neighboring countries in 2024

2 EMT simulation at RTE

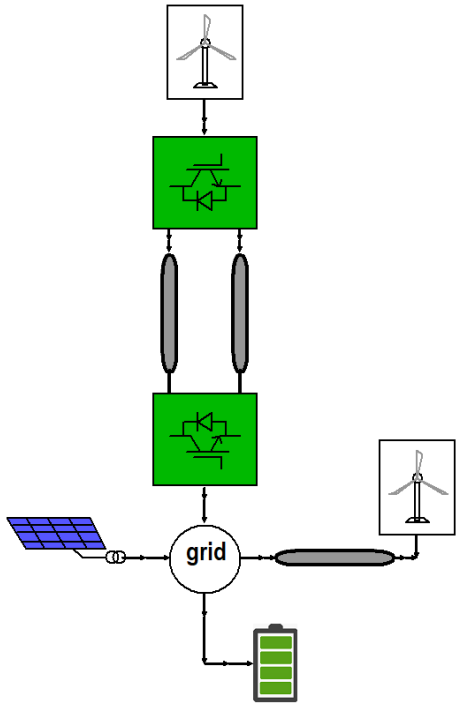
Data, models and studies

An increasing demand for EMT studies

Energy transition → **Massive IBR, Large loads and various connection topologies** → **Increasing demand for detailed studies** → **More data and simulation ressources are required**



Wind and solar energy in the world
Source: Energy Institute



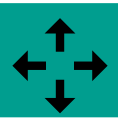
- Switching transient studies
- Insulation coordination
- Temporary overvoltage studies
- **IBR Performance verification**
- **Subsynchronous and torsional interactions**
- **Power Electronics interaction studies**
- Event analysis
- **Harmonic Studies**
- HVDC project review
- **Blackstart**

- Real-code model for control and protection
- Fast simulation
- Easy to use
- Model compatibility
- Model update
- Large grid model handling

Outlook on EMT model integration challenges

Enabling efficient EMT simulation for large and complex systems

Grid Data Portability

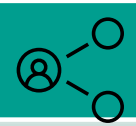


- Data import tool ensuring consistency between grid simulator.
- Standardized format for data portability → Common Information Model (CIM)

Model Performance

- Computationally efficiency
- Accuracy
- Interoperability

Model Accessibility



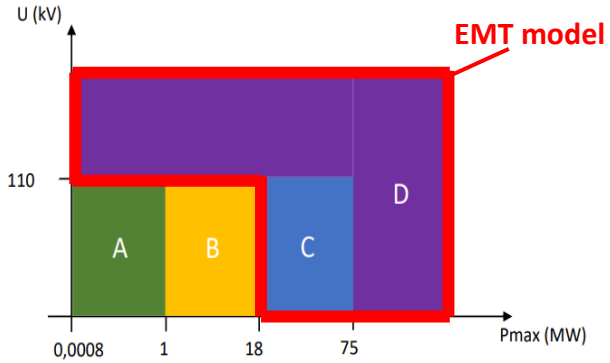
- Model access to multiple stakeholders.
- Confidentiality and compliance with data-sharing protocols.
- Cloud-based solution.

RTE EMT models requirements for IBRs

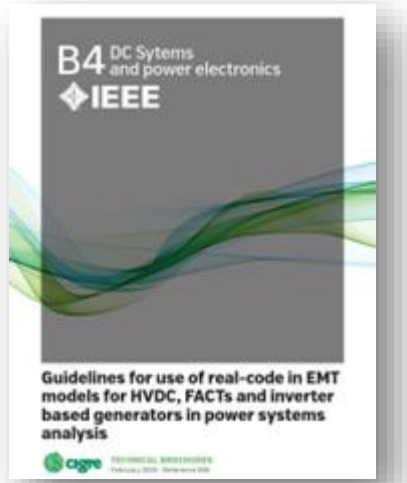
Offline model :

- EMT model developed by Original Equipment Manufacturers
- Type C and D (network code Requirement for Generators)
- Validity frequency range [0.2Hz – 10kHz] – usually reduced to 2.5kHz
- Detailed and open representation of power system component
- P&C model based on real-code using .dll format from CIGRE TB958 : Guidelines for use of real-code in EMT models for HVDC, FACTs and inverter based generators in power systems analysis
- Model documentation

https://www.services-rte.com/en/home.html

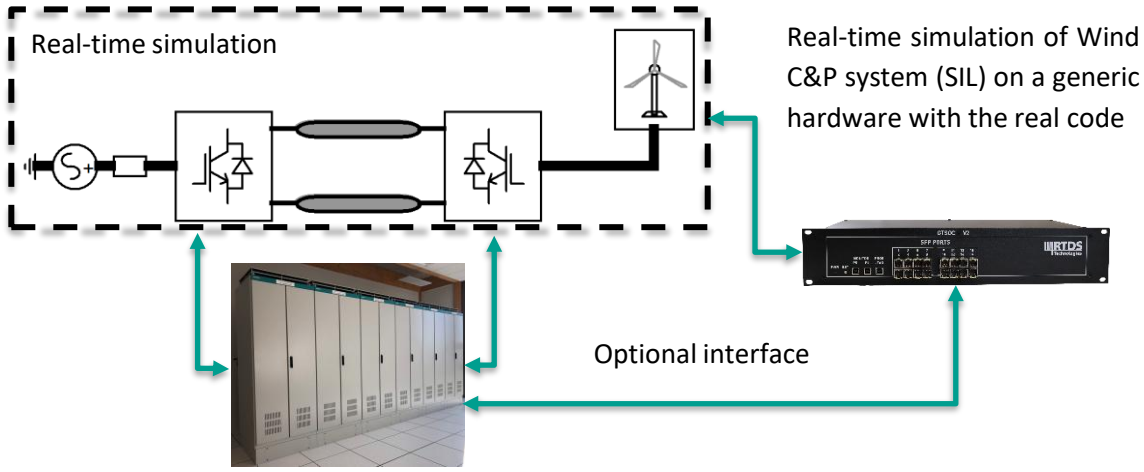


EMT model requirements applied for C & D type PPM in France



EMT real-time simulation (when required):

- Typical application: offshore wind farm connection using HVDC link
- Software In the Loop solution
- Generic hardware using real-code of wind C&P system



HVDC C&P replica: specific hardware and software

Model validity

3 steps model validation process has been applied in the RTE grid code for over five years.

Data validation

- OEM model used for design studies
- Power components are accessible
- P&C model based on dll format from Cigre/IEEE brochure TB958

Simulation-based verification

- Verification of the model transfer from the original model EMT tool to the EMT tool used at RTE
- Validation at various electricals nodes of the installation

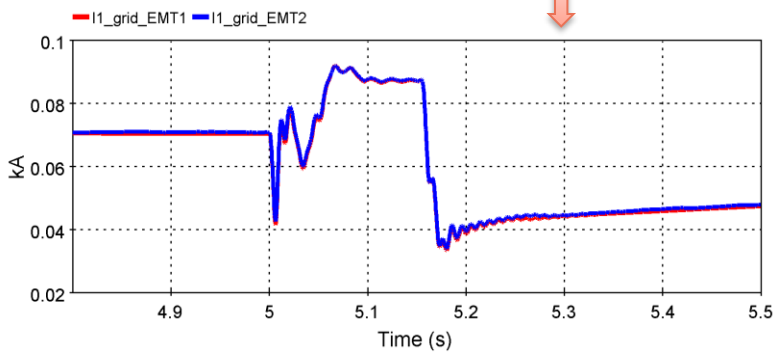
Site tests validation

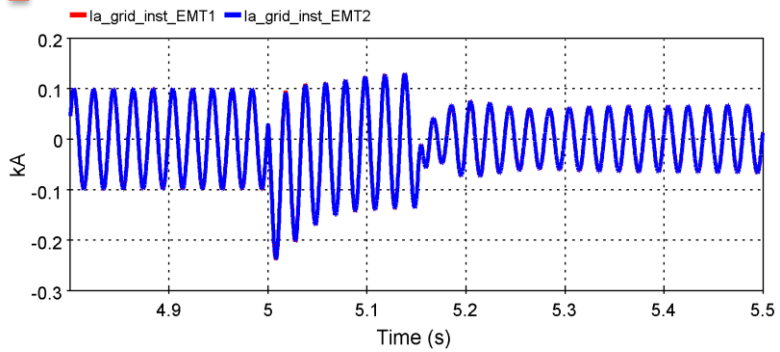
- Validation with site tests
- Validation at the point of common coupling.

Wind Turbine model validation:
Conmparison of results from OEM's EMT tool (PSCAD) to RTE's EMT tool (EMTP)

Zone 1 : Single Unit

Event: 1-phase to ground fault at 66kV wind turbine terminals



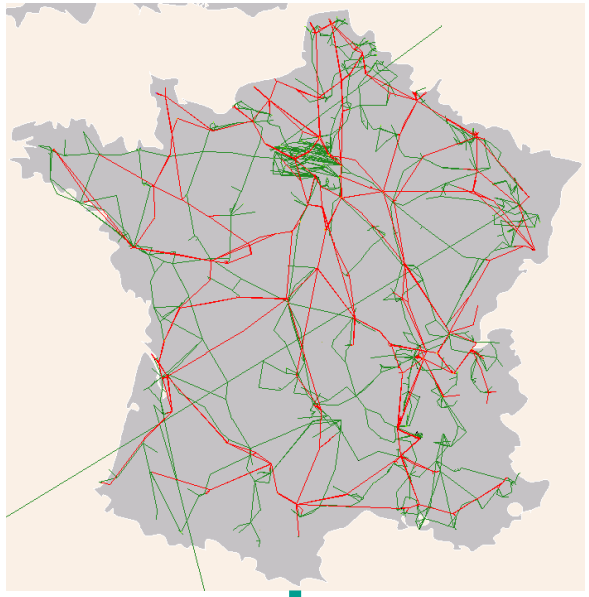


Source: Challenges faced by TSO to specify, test and integrate EMT models of IBRs to support grid stability, Sébastien Dennetiere, Fabien Moerretton, Mickaël Thibert, Elias Mberou, Yannick Vernay, Cigre Trondheim 2025

EMTP model of RTE grid - Implemented solution

Import of network data operational at RTE since 2011

French Grid data in RMS tool



Export

CIM CGMES files

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<cim:ACLineSegment rdf:ID="_AGASSL71ARAMO_ACLS">
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    <cim:ACLineSegment.gch>0</cim:ACLineSegment.gch>
    <cim:ACLineSegment.r>0.03</cim:ACLineSegment.r>
    <cim:ACLineSegment.x>0.18</cim:ACLineSegment.x>
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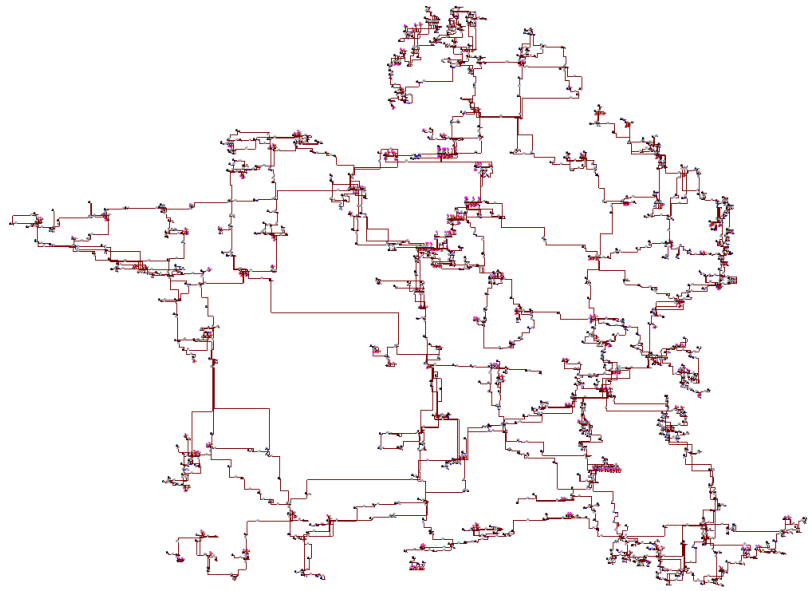
</cim:CurrentLimit>
```

Import

EMTP



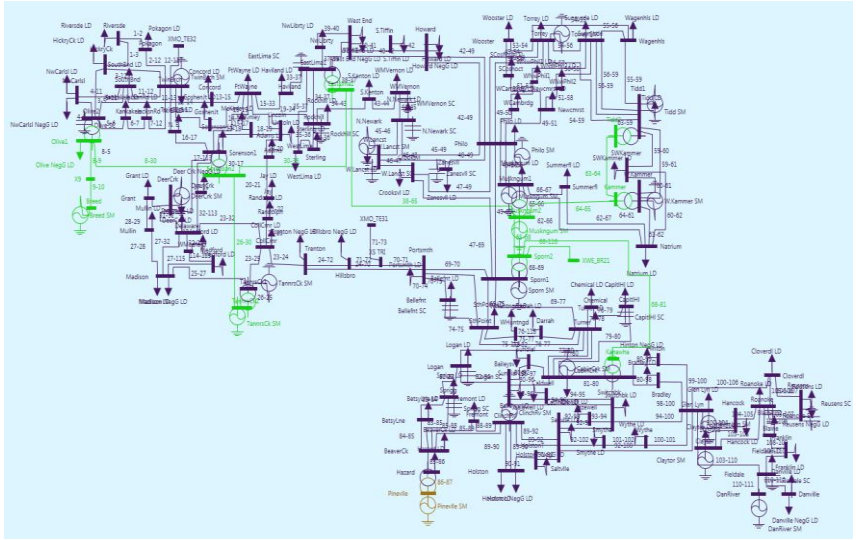
Models used for planning and post event analysis

When EMT studies are requested,
it is **crucial** to use consistent data with studies already performed in RMS tools

Grid Data Portability

Automatic drawing or updating existing grid

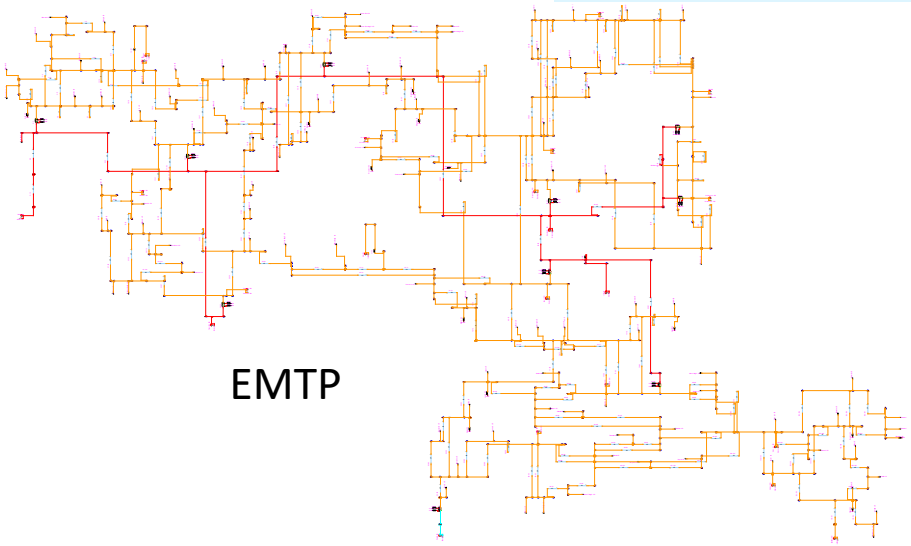
Import of network data



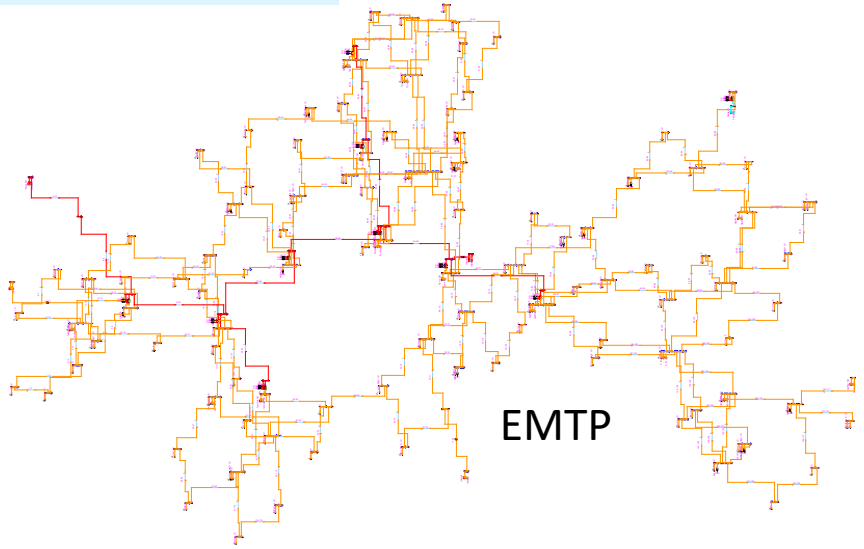
https://www.youtube.com/watch?v=fHRNqh9hJQ0

Importing data within an existing EMT grid model

Import using Auto Layout



EMTP



EMTP

Validation of network data import

Import of network data

When data are imported, a validation process is performed to confirm that data have been correctly imported

Comparison of load-flow calculated in the RMS tool and in the EMT tool is performed

User is informed of import errors

Load-flow comparison (automatically generated)

EMTP Sig	EMTP pos	EMTP Voltage (kVRMSLL)	EMTP Pha	CV Node	CV Voltage	CV Phase	Diff Tensions	Diff Phases	Relative voltage error (%
s4665	CRENEP6	234,6382	-15,7831	CRENEP61	233,8	-15,7	0,8382	0,0831	0,357230835
s3523	ARGIAP6	237,2288	-0,2677	ARGIAP61	238	-0,5	0,7712	0,2323	0,325087005
s14005	TARN5P6	236,8348	-1,2192	TARN5P61	237,6	-1,4	0,7652	0,1808	0,32309441
s12617	MOUGUP6	237,0399	-1,0476	MOUGUP61	237,8	-1,3	0,7601	0,2524	0,320663314
s7196	ROSIEP6	234,7149	-16,5211	ROSIEP61	234	-16,5	0,7149	0,0211	0,304582283
s4047	BARBUP6	234,9935	-21,227	BARBUP61	234,3	-21,4	0,6935	0,173	0,295114546

EMTP results

RMS results

Differences between EMT and RMS
→ should be small

Import Error Report

Error Type	Object Type	Substation Name	Description
Error	Substation	CANTEP7	Pb Convergence: the shunt compensator has no ...
Info	Substation	CHEV5P6	The machine CHEV5.TC2 is in PQ mode...
Warning	Substation	CHEY6P7	Pb Convergence: CHEY67G2 has Pcons = 0

Large grid data imported in EMTP

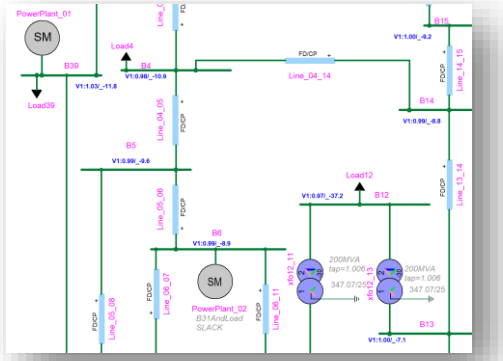
For time domain and frequency domain simulations

Grid and equipment data imported in EMTP

CIM CGMES format

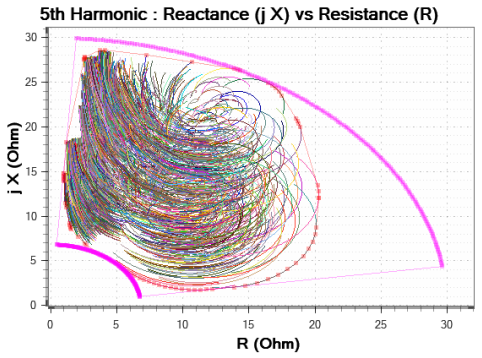
Initialization of time-domain simulation and validation of data import

Load-flow simulation



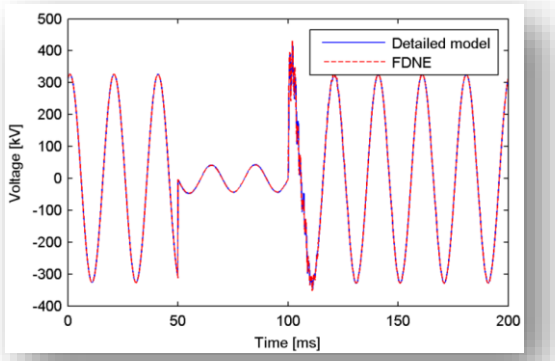
Harmonic amplification studies and provision of harmonic loci

Frequency domain simulation



Dynamic simulation

Time domain simulation

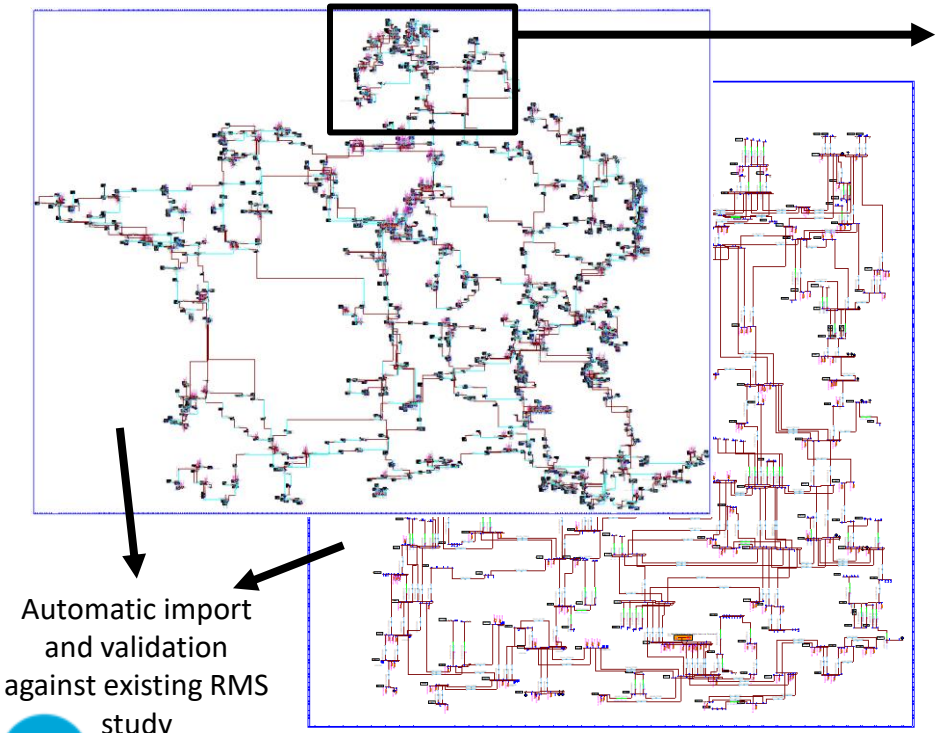


Harmonic amplification study and harmonic loci provision

Example: AC connection of offshore wind park
Harmonic study (not time domain) to:

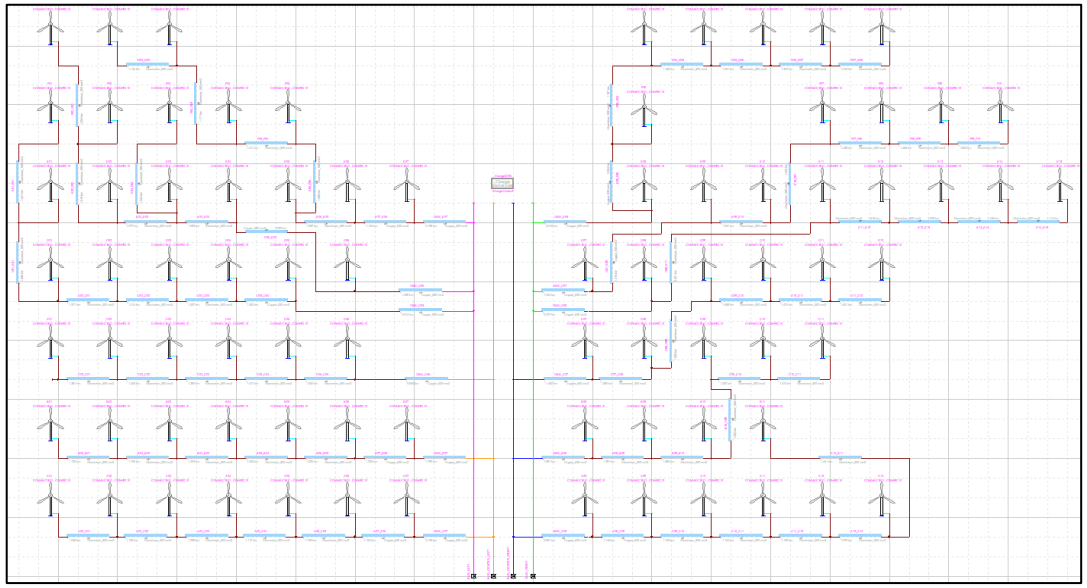
- assess the onshore background harmonic amplification to design onshore filter
- calculate onshore harmonic impedance loci from rank #1 to #50 to be shared with wind developers

Harmonic study is done with the same tool and same set of data than EMT time domain to ensure data consistency



Automatic import and validation against existing RMS study

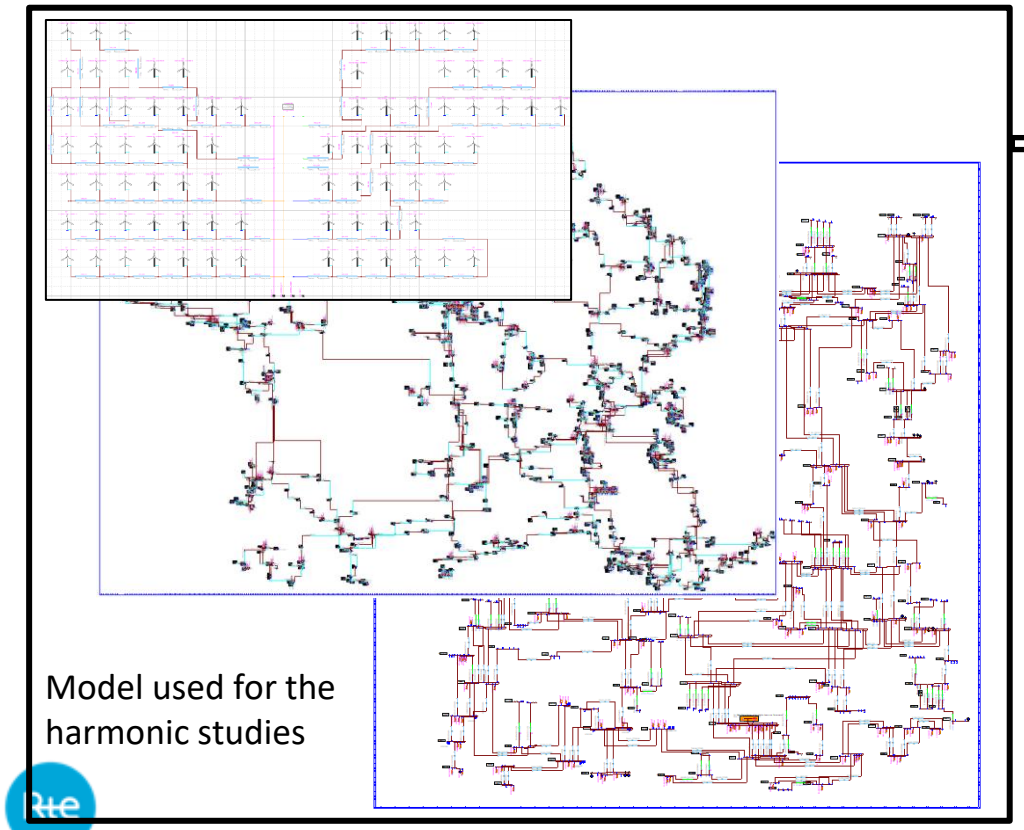
The local 225kV grid close to the Wind farm connection is manually modeled with frequency dependant cable/line models
The offshore grid is modeled in detail with the cable arrays data and connected to the entire model



EMT study with frequency dependant network equivalent

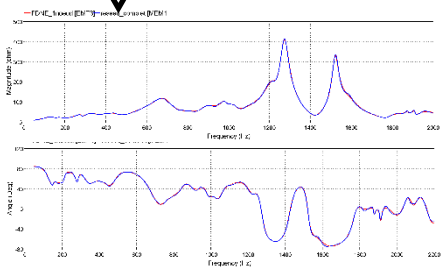
Example: AC connection of offshore wind park – transformer and filter energization nearby the wind farm connection
Time domain study to:

- Evaluate risk of temporary / switching overvoltage
- Propose counter measures

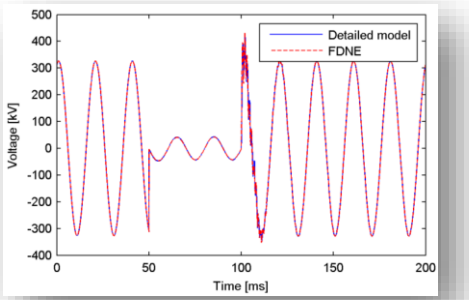


Model used for the harmonic studies

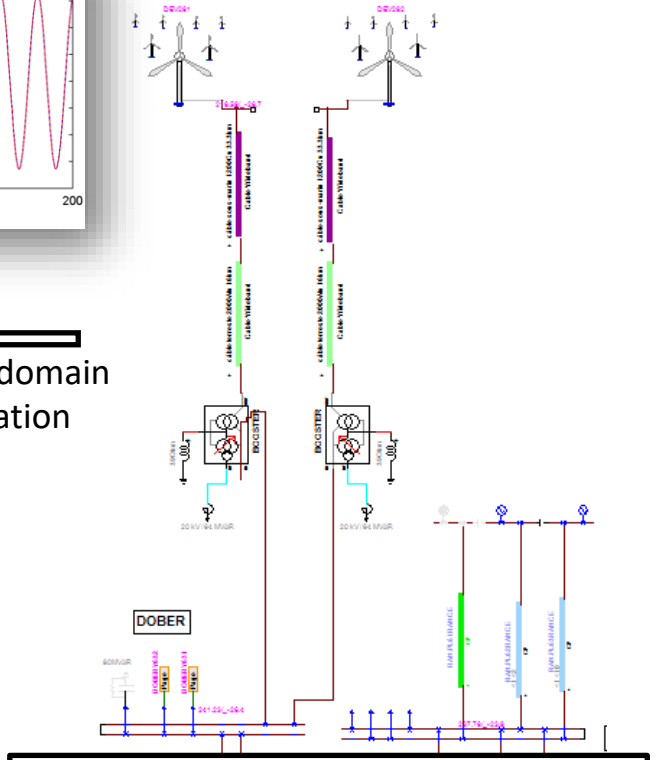
Harmonic impedance at the point of interest



Fitting process to get time domain equivalent circuit in state space format
(Frequency Dependant Network Equivalent)



Time domain simulation



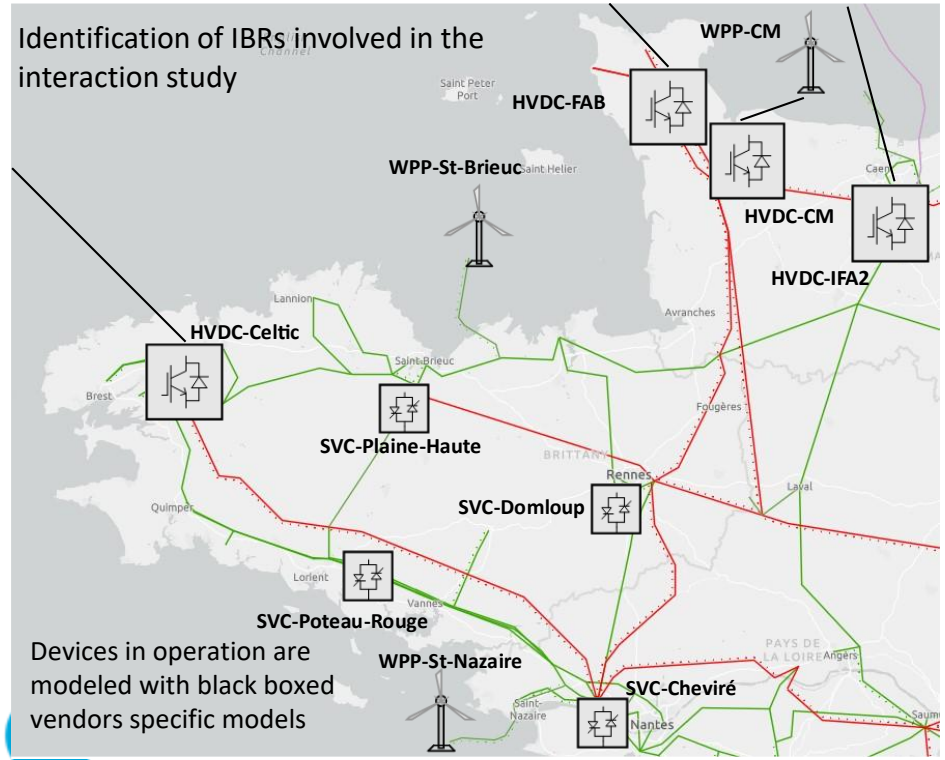
FDNE

CELTIC HVDC – interaction study

Connection of a 700MW VSC converter station with GFM controls
Screening study to identify risk of interactions with Converter Based Units (**Extended MIIF criteria defined in CIGRE TB934**)

EMT Time domain study to:

- Evaluate risk of adverse interactions with the pre-identified assets
- Evaluate possible counter measures in collaboration with the HVDC OEM (SIEMENS Energy)



EMT model imported from the LF simulation tool

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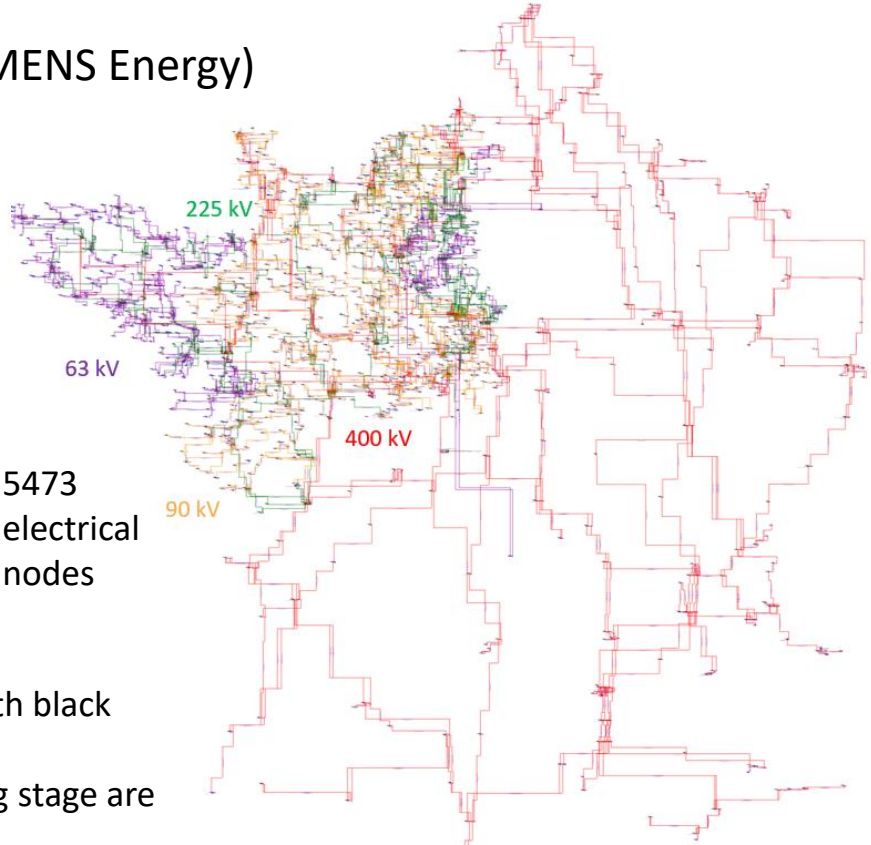
Devices in operation are modeled with black boxed vendors specific models
Devices in construction or at planning stage are modeled with generic representation

5473 electrical nodes



EMTP model of the grid used for the EMT interaction study

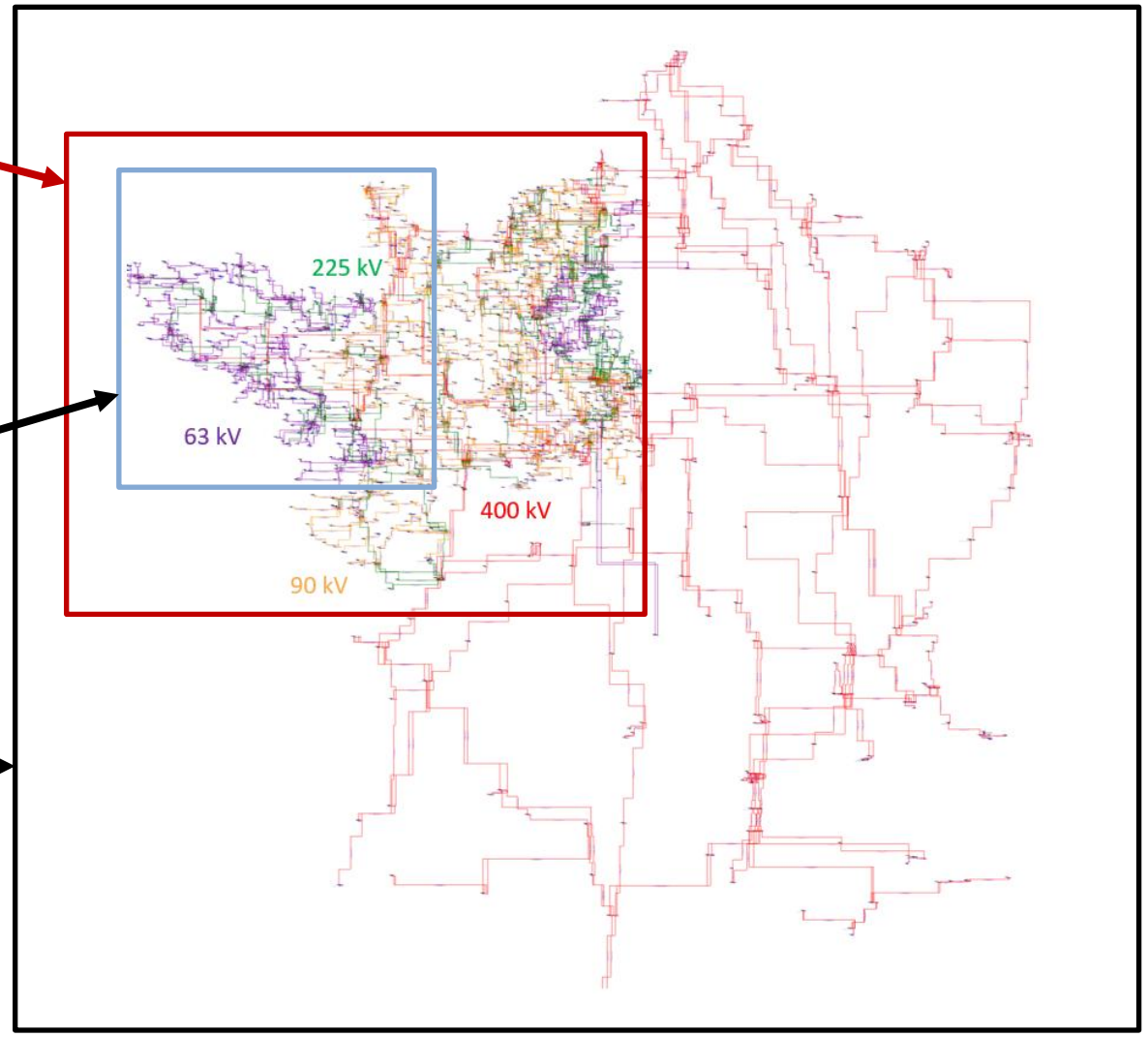
CELTIC HVDC – interaction study

Parallel computing architecture

1 CPU for 225/90/63kV grid solution

9 CPU for IBR solution
41 DLL, Multi-time step

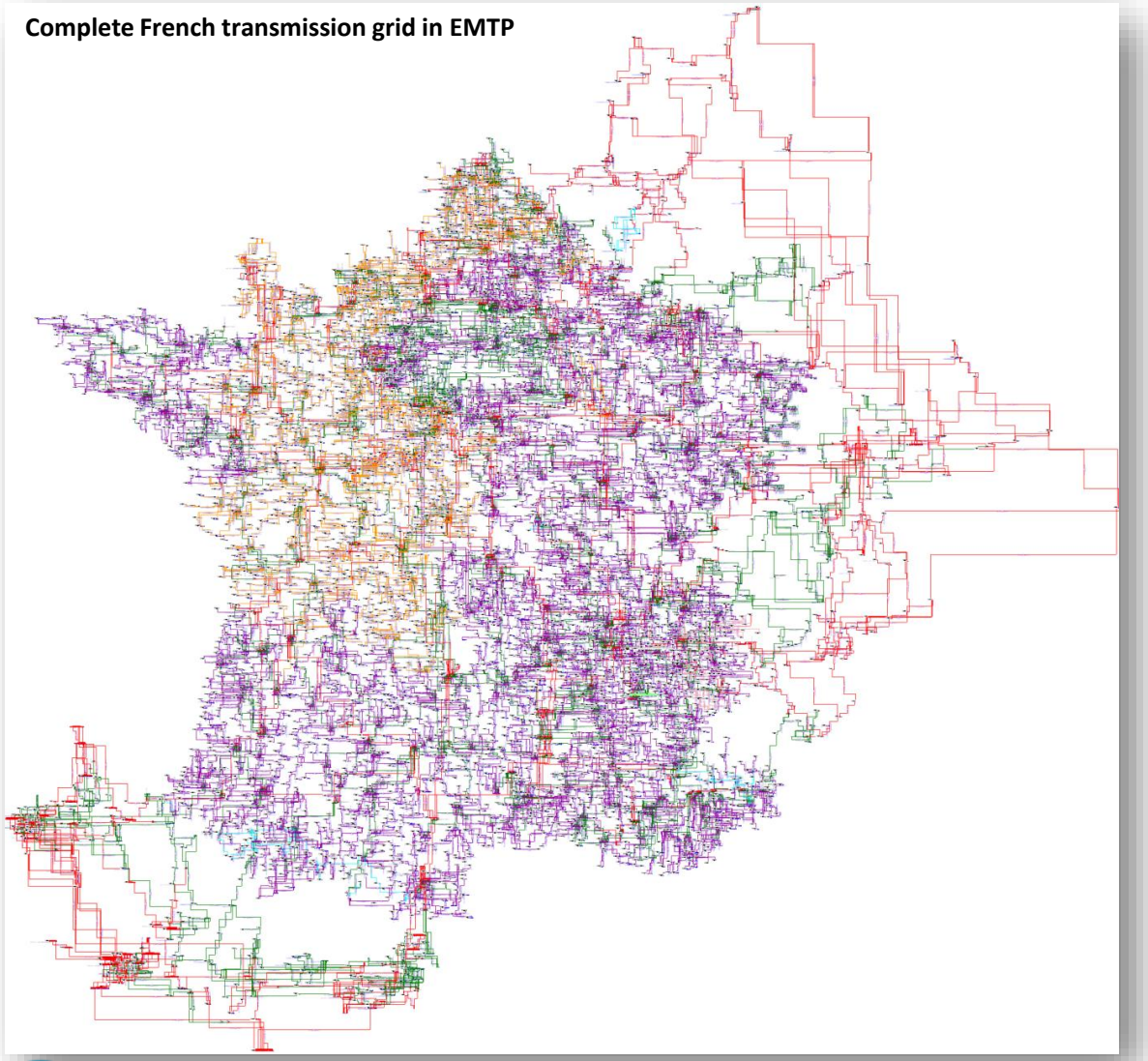
1 CPU for 400kV grid solution



Simulation (20 s)	Time (s)
Reference (1 core)	21,744s (6h)
Parallel (11 cores)	1140 (19min)

The simulation architecture has 64 cores with 128 logical processors, AMD Ryzen Threadripper PRO 5995WX @ 2.70GHz

Very large EMT models – linear model



Entire French Transmission grid including 400kV, 225kV, 90kV and 63kV + reduced grid of surrounding countries

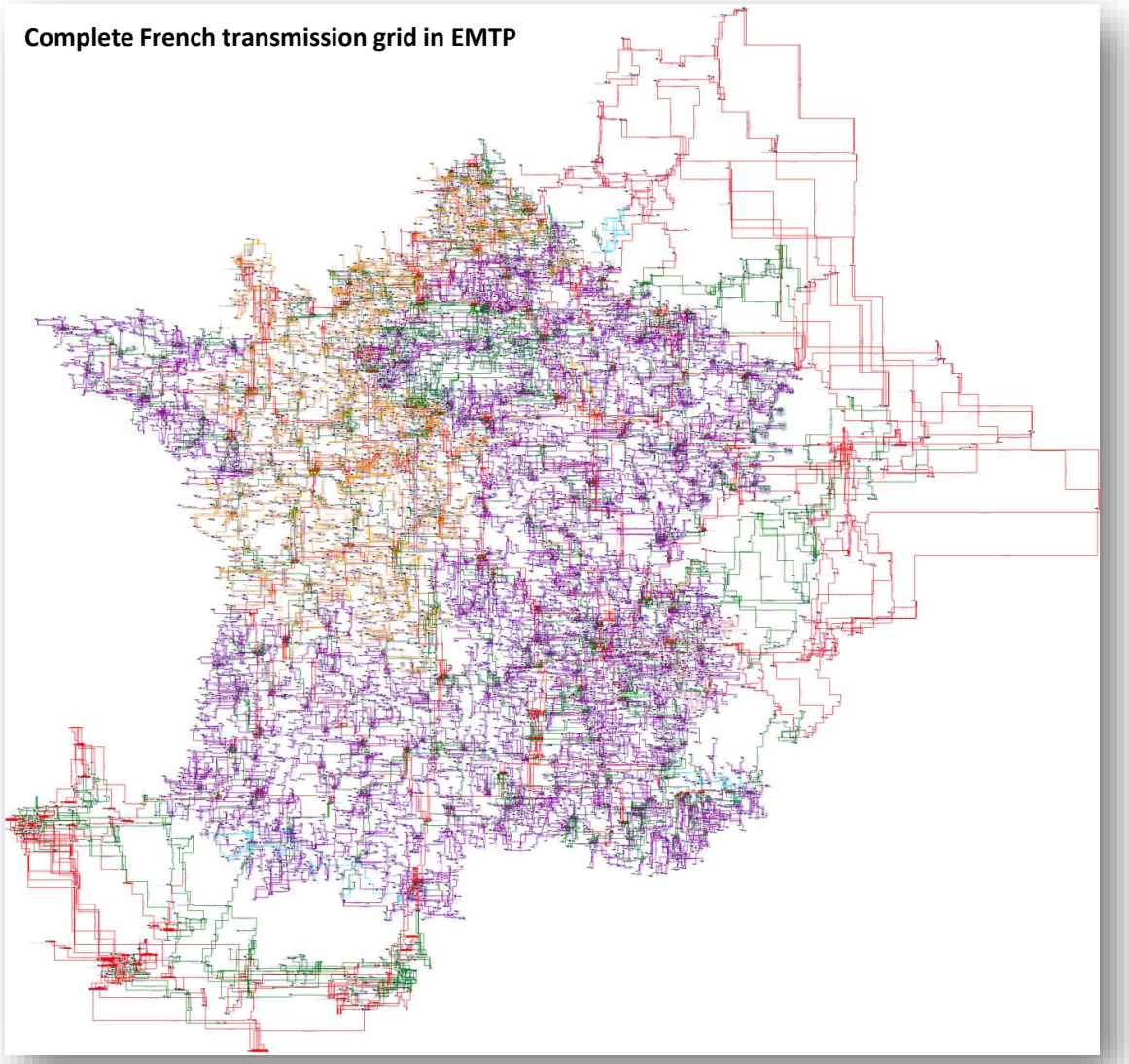
Items	Number
3ph network nodes	25 244
Size of the main system of equations	126 454
Devices	58 358
Transmission lines (3ph)	8 564
Generators (3ph)	13 121

Timings (64 bits version)	Time
Import from CIM to EMTP user interface	2h33
Load-flow	33s
Time domain simulation (1s, 50µs) 1 core	11min

CPU : AMD Ryzen Threadripper PRO 5995WX @ 2.70 GHz

Source: B. Bruned, C. Martin, "The EMT simulation of a very large-scale network: the complete French Transmission Grid," Contributions of CIGRE Paris Session, 2024.

Very large EMT models – with nonlinearities + SG + HVDC



Entire French Transmission grid + transformer saturations + synchronous machine modelling + HVDC links

Items	Number
3ph network nodes	25 824
Size of the main system of equations	129 185
Saturations (nonlinear inductances, 1ph)	4725
Synchronous machines + Ctrl	40
HVDC links	7

Timings (64bits version), 1s, 50µs	Number of cores	Time
64bits Version	1	47min
64bits Version Optimized	5	8min

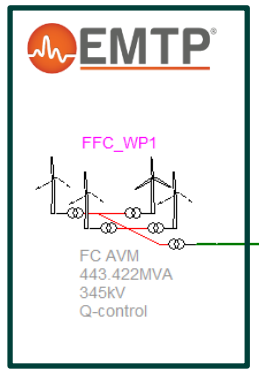
CPU : AMD Ryzen Threadripper PRO 5995WX @ 2.70 GHz

Source: B. Bruned, C. Martin, A. Petit, "Large-scale Electromagnetic Transient Simulation of the French grid: Challenges and Solutions," submitted to Symposium CIGRE Trondheim 2025.

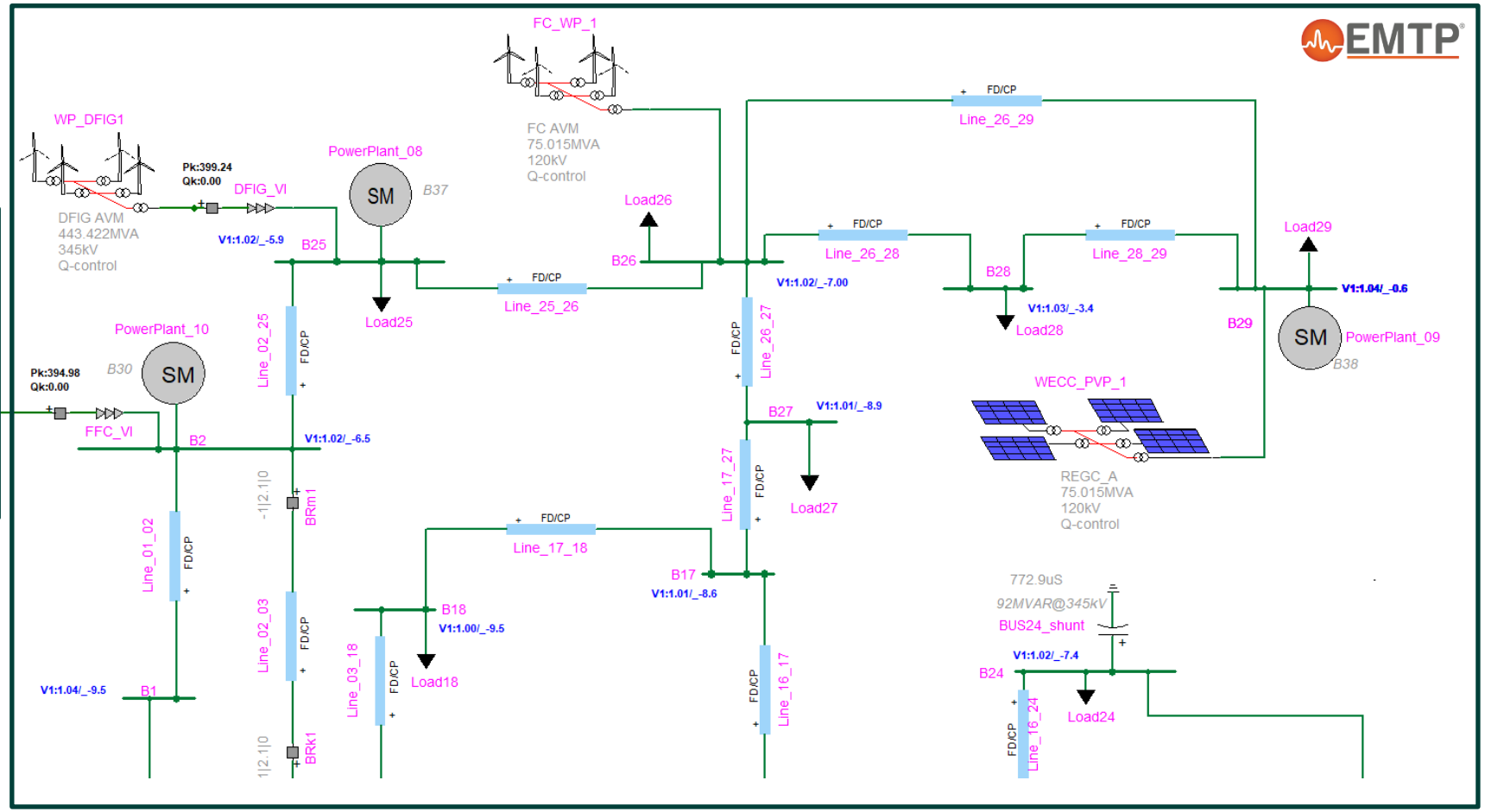
EMT Connection Tool concept

Integration of new Converter Based Units → RTE is in charge of interaction studies

Why Grid Model cannot be shared? → confidentiality of models + identification of network constraints



EMT model provided by customer



Grid model maintained by RTE with vendors specific models

Accessibility of the grid model to external stakeholder for **preliminary interaction studies** and **fine tuning when issues are detected**

→**EMTP connection tool**

EMT Connection Tool concept – Step1

Azure

EMTP connection tool – Online interface

Equipment models prepared
by External Party (local PC)
+
list of scenario to be simulated
(ConfigA/Config1, ConfigA/Config2…)

External Party Side

EMTP

Config A

Config B

Config C

FFC_WP1

FC AVM
443.422MVA
345kV
Q-control

Grid models prepared by RTE (local PC)

RTE

EMTP

Config1

Config2

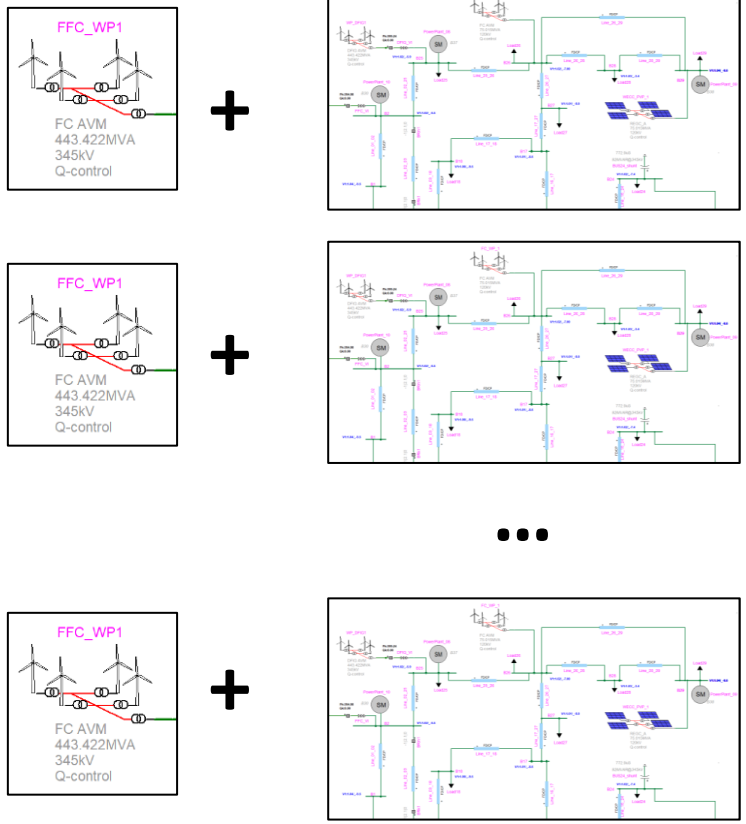
Config3

Config4

Config5

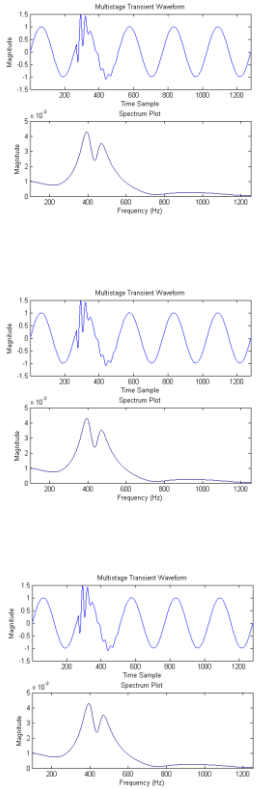
EMT Connection Tool concept – Step2

Azure



Models merging
(no fictitious delay required between models)

Simulations running on VMs



Simulation results

Results available for download by the External Party

Actions done automatically on the Azure Server

3 Conclusions

Perspectives for reliable large EMT studies

Large Grid EMT simulation at RTE

Challenges:

- Time domain studies involve an increasing number of IBR → increased complexity and system size
- Simulation results shall be provided within a short period of time to limit impact of projects execution
- Data consistency between load-flow, harmonic and time domain studies is crucial
- Power system engineers shall be concentrated in performing studies rather than building network models

Objectives of ongoing initiatives:

- Fast and accurate Large scale power system modeling in time domain and in frequency domain
- Facilitate development of network models and reduce risk of errors
- Give access of large EMT models to external entities (suppliers, market participants)

Improvement in IBRs models are still required

Improvements in specifications

- Many on-going initiatives (ENTSO-E, CIGRE/IEEE,…)
- To cover different topics:
  - accuracy (i.e., the minimum level of details);
  - interoperability between models provided by different vendors;
  - maintenance and update;
  - simulation speed

Improvements in models

- Better representation of C&P hardware in the model
- Standardization of code interfaces (CIGRE B4.82) for Black box C&P models
- Improved solutions to facilitate maintenance of models
- The Digital Twin concept can support improvements in models

Large integration of renewables/HVDC – InterOPERA experience

Long-term use:
- extension of the grid
- replacement
- post-event analysis

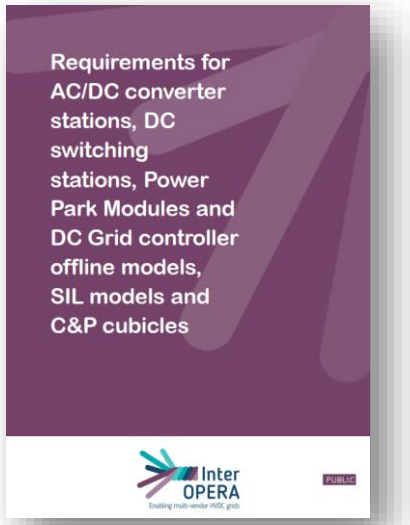
Tool independant C&P models
Documentation of interfaces

C&P model
based on the IEEE/CIGRE DLL guideline B4-82

Performing tests with different vendors' models with the same simulation tool

Sharing models and results

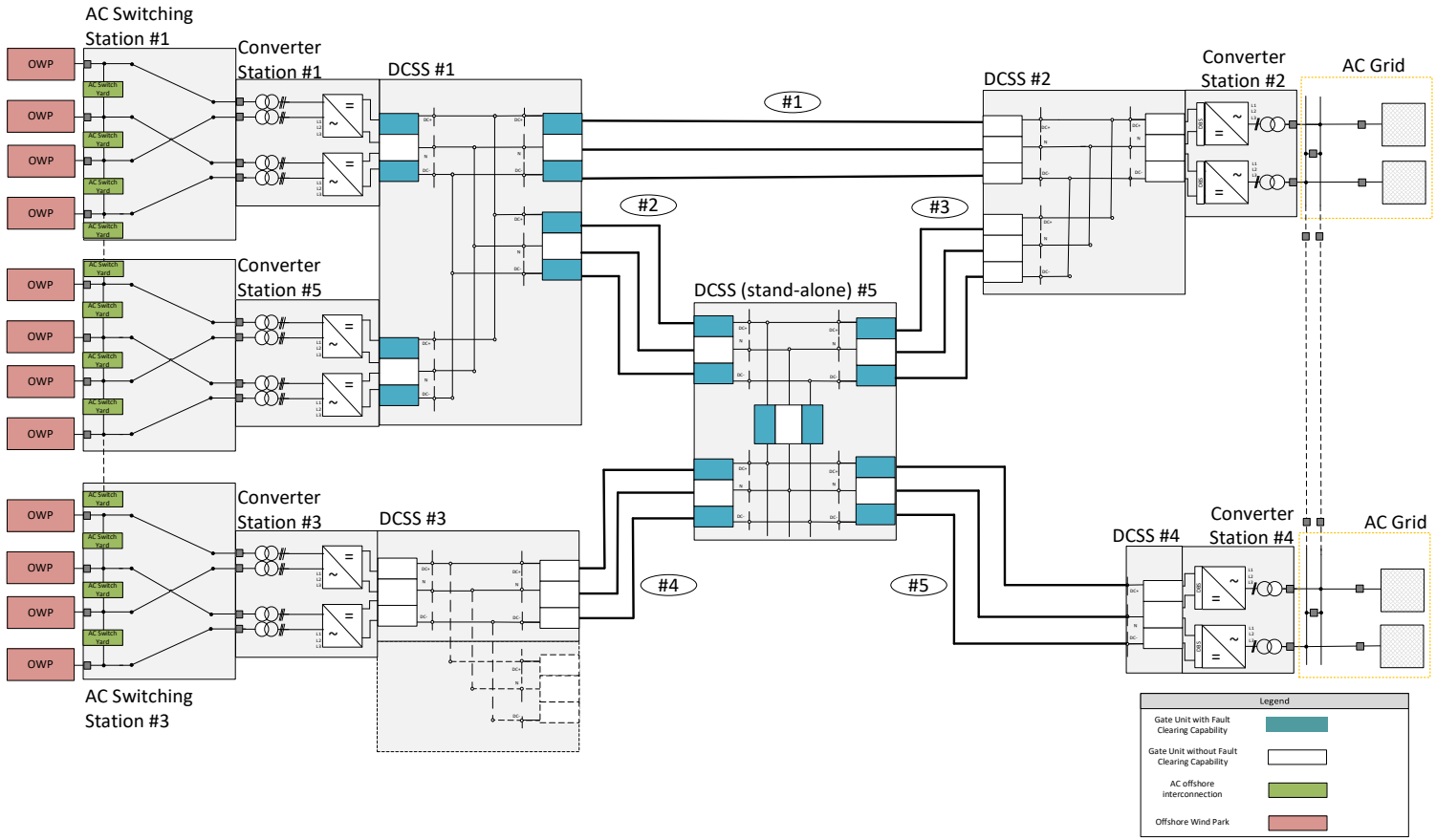
Balance between confidentiality *(to respect vendors' IP)*
and accessibility *(for the system integrator to perform the tests)*
→Clear requirements on data accessibility



InterOPERA D1.1
https://interopera.eu/publications/

HVDC grid model for the InterOPERA project

Objective of the study: testing interoperability of the Multiterminal Multi vendor system
HVDC models in EMTP and PSCAD provided by SIEMENS Energy, Hitachi Energy and GE Vernova
Wind Farm models in EMTP and PSCAD provided by VESTAS and SGRE
All vendors provide C&P models compliant with the IEEE/CIGRE interface



Le réseau
de transport
d'électricité

Thank you !