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TenSyGrid

Powering the Transition to 100% Renewable Energy

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The transition to renewable energy is fundamentally reshaping how power systems behave – and challenging the tools used to keep them stable. ***TenSyGrid*** *tackles this emerging problem head-on by developing a new generation of tensor-based analytical methods designed for electricity grids powered almost entirely by power-electronic converters.*

Across the world, electricity systems are undergoing one of the most profound transformations since their inception. Driven by climate targets, energy security concerns, and rapid technological innovation, power grids are shifting toward ever higher shares of renewable energy sources such as wind and solar. These sources are largely connected to the grid via static power-electronic converters rather than traditional synchronous generators. While this shift enables cleaner electricity, it also fundamentally changes how power systems behave.

UNLOCKING STABILITY IN CONVERTER-DOMINATED POWER GRIDS

The TenSyGrid project – Tensors for System Analysis of Converter-Dominated Power Grids – was launched to address one of the most critical challenges emerging from this transformation: how to reliably analyse and ensure the stability of future power systems dominated by power electronics. The TenSyGrid team at the University of Malta includes Prof. Ing. John Licari as Principal Investigator, Prof. Ing. Cyril Spiteri Staines and Prof. Alexander Micallef as senior researchers, and Dr Ing. John Caruana and Ing. Brian Micallef as RSOs. Coordinated by Fraunhofer IWES and backed by a strong European consortium, TenSyGrid aims to provide grid operators and engineers with an innovative analytical tool that enables direct methods for assessing stability in the real-time operation of future large-scale power networks – namely, those powered entirely by renewable energy.

WHY TODAY'S POWER SYSTEM TOOLS ARE REACHING THEIR LIMITS

The traditional analytical tools used for power systems were developed for grids dominated by large, comparatively linear synchronous generators. These generators supply inertia to the power system by converting mechanical energy into electrical energy. Their dynamic behaviour has been extensively studied and is well understood. In contrast, modern converter-based resources such as wind and solar are programmable, fast, and highly nonlinear. Their controls interact across a wide frequency range – from slow system-wide dynamics to high-speed electromagnetic phenomena.

Today's industry-standard tools rely heavily on simplified simulations or linearised models. While computationally efficient, these methods often fail to capture critical nonlinear interactions in new, converter-dominated networks. At the other extreme, detailed simulations can represent these effects accurately. However, their large computational burden makes them impractical for large-scale or real-time studies.

As a result, system operators are forced to be conservative. For example, they must impose limits on instantaneous renewable penetration – that is, the amount of power that renewables provide to the grid. This is not because renewable generation is unavailable, but because analytical tools cannot yet guarantee stability beyond certain thresholds. TenSyGrid directly tackles this bottleneck.

A NEW PERSPECTIVE: MULTILINEAR MODELS AND TENSOR MATHEMATICS

At the heart of TenSyGrid lies a novel mathematical approach based on hybrid implicit multilinear time-invariant models and tensor decomposition. Multilinear models occupy a unique middle ground between the efficient, simple linear models and the computationally demanding, fully nonlinear models. They are rich enough to capture key nonlinearities inherent in power-electronic converters, while remaining structured and computationally efficient.

Crucially, multilinear models can be represented as tensors – mathematical objects that generalise matrices to higher dimensions. These are interpreted via modern tensor decomposition techniques, which

The UM TenSyGrid Team from left to right: Prof. Alexander Micallef, Ing. Brian Micallef, Prof. Ing. John Licari, Dr Ing. John Caruana, Prof. Ing. Cyril Spiteri Staines
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allow these high-dimensional objects to be stored and analysed in compact, simpler forms. This dramatically reduces computational complexity and enables the analysis of very large systems.

By transforming complex, nonlinear power system equations into structured, multilinear tensor representations, TenSyGrid opens the door to analytical stability assessments that were previously infeasible at scale.

FROM BLACK BOXES TO INTERPRETABLE MODELS

Another pressing challenge in modern power systems is the widespread use of 'black-box' models supplied by equipment manufacturers. The methodology and inner workings of these models are hidden from users. While they protect intellectual property, they limit system operators' ability to understand the root causes of instabilities or unexpected behaviour.

TenSyGrid is addressing this issue by developing interpretable system identification methods for converter-dominated systems. Instead of relying on artificial intelligence and machine learning methods, the project's multilinear framework produces structured models whose parameters can be meaningfully interpreted. This enables engineers to trace how specific components or interactions influence system stability – an essential capability for real-time operation and post-event analysis.

THE TENSYGRID TOOLBOX: FROM THEORY TO PRACTICE

All methodological advances in TenSyGrid converge in the development of the TenSyGrid Toolbox. This software framework builds upon the existing open-source MTI Toolbox developed by one of the partners (Hamburg University of Applied Sciences) and extends it with power-system-specific capabilities.

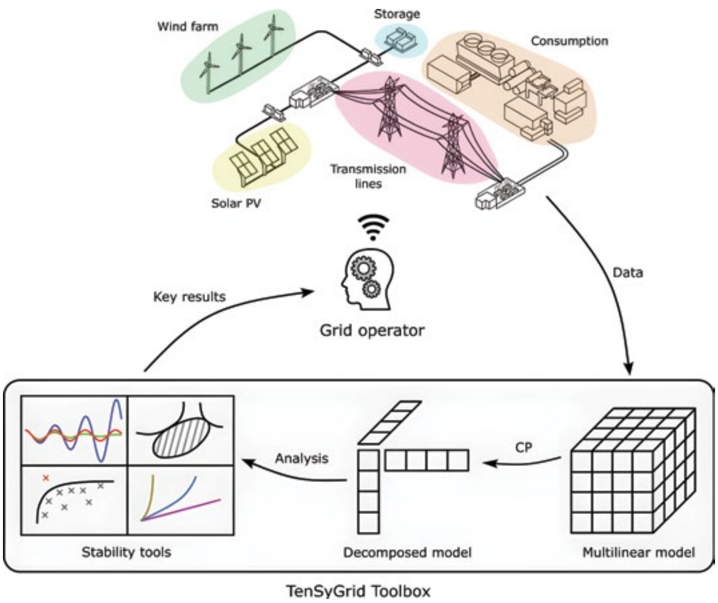
Key features of the toolbox will include:

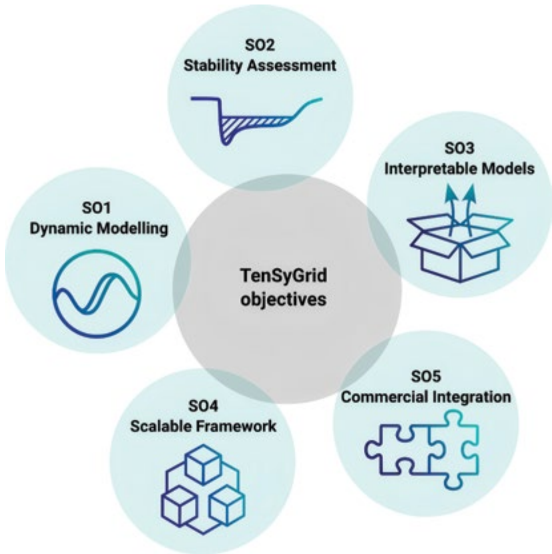
- A **library of multilinear power system component models**, covering converters, generators, loads, High-Voltage Direct Current (HVDC) links and storage systems.
- **Direct stability assessment methods** that extend beyond classical analytical methods and are applicable under high levels of renewable penetration.
- **Scalable and interpretable models** that can adapt as grid topology and operating conditions change.
- **Compatibility with commercial software** widely used by practitioners to ensure seamless integration into existing workflows.

The toolbox will be designed with real-world applications in mind. It targets both offline planning studies, such as grid expansion scenarios, as well as real-time operational support, where computational speed and interpretability are paramount.

VALIDATED ON REAL NETWORKS

To ensure practical relevance, TenSyGrid places strong emphasis on validation using realistic power system





Left: An overview of the TenSyGrid Toolbox and its connection with the grid operator, enabling advanced analysis of converter-dominated power systems.

Right: The key objectives of the TenSyGrid Project

Images by eRoots

models. Case studies range from mid-size benchmark systems to large-scale national networks, including detailed studies of the Maltese power system and scenarios approaching 100% renewable penetration.

These demonstrations are complemented by close collaboration with transmission and distribution system operators (Enemalta, KEPCO, RTE), software vendors (MATLAB and IPSA), and technology providers (OPAL-RT) across Europe and beyond. Feedback from these stakeholders ensures that TenSyGrid's methods address real operational challenges rather than purely academic problems.

IMPACT BEYOND THE PROJECT

By the end of the project in 2027, TenSyGrid aims to reach a technology readiness level of 5, having demonstrated its tools in relevant operational environments. The long-term vision extends even further: to establish multilinear and tensor-based analysis as a new paradigm for power system stability assessment.

In a world racing towards climate neutrality, the ability to understand, analyse and actively control converter-dominated power grids will be decisive for the success of the energy transition. As electricity systems move closer to 100% renewable energy operation, stability can no longer be ensured by simplified models or overconservative operating margins. TenSyGrid responds to this challenge by providing a robust new set of lenses through which the future power system can be analysed clearly and efficiently.

By combining multilinear modelling, tensor mathematics, and close collaboration with power grid operators, TenSyGrid equips engineers with practical tools to operate future grids safely, efficiently, and with confidence. In doing so, it not only removes a key technical bottleneck for high renewable penetration but also lays the foundation for a new paradigm in power system analysis – one capable of supporting the resilient, flexible and fully renewable electricity networks of tomorrow.

The TenSyGrid project is coordinated by the Fraunhofer Institute for Wind Energy Systems and involves leading contributors, including Universitat Politècnica de Catalunya, eRoots Analytics, Hamburg University of Applied Sciences, and the University of Malta. Further information can be obtained from the dedicated project website at tensygrid.eu or by contacting the UM principal investigator directly at john.licari@um.edu.mt.

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