Synopsis – Project SAFEr Grid (Store-And-Forward Energy Grid)

The ERC Synergy Grant project SAFEr Grid is a bold response to the urgent challenges faced by today's power systems. By breaking with the century-old principle of synchronism and replacing it with asynchronous energy coordination, the project rethinks the foundations of power system organization, control, and governance. Its mission is to provide a blueprint for a resilient, scalable, fully automated, and decarbonized energy supply based on distributed Renewable Energy Sources (RESs).

For over a century, power systems have operated on the principle of global synchronism, maintaining a tightly coupled grid frequency by balancing power generation and consumption. Large centralized and inertia-rich fossil-fuel-driven generators and tight centralized control mechanisms made this possible. However, the global shift toward decarbonization, driven by the widespread integration of RES primarily in the form of Inverter-Based Resources (IBRs), is fundamentally disrupting this legacy model and challenges traditional assumptions about power system dynamics, stability, and control.

As power systems evolve into decentralized IBR-dominated infrastructures with low-inertia, the principle of global synchronism—once a key technical strength for stable power system operation—is now becoming a systemic vulnerability. Sudden fluctuations in power generation or consumption, or local fault events, can cause frequency deviations that propagate quickly throughout the infrastructure, jeopardizing overall power system stability. The 2016 South Australia blackout and the recent 2025 Peninsular Spain blackout show that local incidences can easily cascade into widespread outages. This highlights the growing fragility of synchronous operation of today's power systems.

In response to this grand challenge, prior research and engineering efforts have largely focused on augmenting the conventional system through advanced measures such as virtual inertia emulation, grid-forming controls, demand-side management, operational flexibility, and revisited power system standards. These approaches strive to integrate distributed renewables into the existing system more effectively while preserving the foundational assumption of synchronous and instantaneous power balancing. Yet these measures face scalability limitations and may prove insufficient to prevent severe blackouts. Moreover, it is unclear whether billions of investments in upgrading the current grid infrastructure can truly solve the fundamental challenge. This raises the question of how it will be possible to adapt the more than one century-old paradigm of synchronism to the constantly changing landscape of today's power systems and master the gradual transition toward a decentralized power system that comprises many small, intermittent producers interfaced via IBRs.

The SAFEr Grid project proposes a transformative and highly disruptive solution to this question. Rather than incrementally adapting the legacy system, the project provides the fundamental research for a radically new operating principle for low-inertia, IBR-dominated power systems: abandoning the requirement of synchronism and replacing it with the concept of asynchronous energy balancing. By leveraging the programmability of IBRs and the growing availability of energy storage, SAFEr Grid thereby envisions power systems as compartmentalized, modular system-of-systems that are composed of autonomous but interlinked subgrids, referred to as asynchronous grids (a-grids). Building on the idea of a multi-microgrid setup, each a-grid operates autonomously with its stability managed purely locally and without dependence on a global system-level frequency.

This concept draws inspiration from another very successful asynchronous system: the Internet with its layered and highly modular architectural design. Just as the Internet routes data between loosely coupled subnetworks, SAFEr Grid envisions energy routing among a-grids via programmable, power-electronics-based devices called energy routers. These energy routers are the decoupling elements between multiple a-grids that implement a store-and-forward-like routing logic for energy. Energy routers buffer and dispatch energy within and between a-grids as needed, thus separating single a-grid operation from the rigid requirement of global synchronism and power balance. At scale, a governing framework, again inspired by the successful role models, abstraction principles, and established protocols of the Internet, will coordinate energy flows across the entire system of a-grids, combining scalable algorithms and economic incentives to maintain stability and efficiency of energy dispatch and supply.

Central to this transformation is a completely new role for power electronics devices. Traditionally considered as unsuitable for managing large and complex system dynamics, power electronics devices will now become the backbone of the envisioned asynchronous power system architecture. Acting as both storage interfaces and routing nodes, energy routers will be controlled not by frequency signals, but by discrete, energy-based control signals that reflect real-world physical and economic conditions. These components are being prototyped during the project using smart transformers, battery storage, and multi-port converter technologies. Alongside this hardware development, the project is further creating new control algorithms and a modeling framework that integrates physical system dynamics with concepts from communication and information theory. The result of this research is a cyber-physical power system model that necessitates the development of completely new theories of power system dynamics, stability, and control.

It is important to stress that SAFEr Grid is not just a technical innovation, as it also introduces a new socio-economic framework for managing power systems. The project envisions an open, layered ecosystem where stakeholders along the entire energy value chain, such as producers, consumers, grid operators, technology providers, and regulators, co-create value. Much like the digital economy enabled by the Internet, the architecture and control principles of SAFEr Grid support a diverse ecosystem of services, pricing mechanisms, and business models. This also entails a reallocation of investment patterns reflecting the economics of RES, moving from operational expenditure toward capital-intensive infrastructures. These shifts further necessitate a robust governance model balancing openness and flexibility with the need for coordination, stability, and security. It must incentivize innovation without undermining trust and reliability. Thus, SAFEr Grid will develop a multi-layered governance structure. Stakeholder analysis and participatory design approaches help to understand user needs, anticipate adoption barriers, and guide the development of open standards and policies.

The paradigm shift enabled by SAFEr Grid not only enables the seamless integration of RES at scale but also catalyzes innovation across the energy sector. Through a synergistic and interdisciplinary research approach, SAFEr Grid defines a highly transformative pathway that will safeguard the security of energy supply in the future: from synchronous power systems governed by an instantaneous power equilibrium to a fully asynchronous architecture based on store-and-forward energy dispatch.