HPC-enabled digital twin for modern power networks

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Abstract – This article presents the development of a High-Performance Computing-enabled Digital Twin (HPC-DT) as an innovative solution designed to significantly enhance real-time power system management for grid operators. It begins by providing a comprehensive overview of the HPC-DT architecture, detailing its key components and the technical methodology for integrating the digital twin with actual power systems. Following the architectural discussion, the article introduces a suite of specialized tools, many of which leverage the computational power of HPC systems, to illustrate the practical capabilities of the proposed concept.

1. Introduction

The energy transition towards 100% renewable energy systems necessitates innovative tools to support power system operators in managing networks, particularly in light of the challenges posed by replacing conventional synchronous generation with power electronics (PE)-interfaced renewable energy systems. These PE assets, which are increasingly being integrated into the system, fundamentally differ from conventional synchronous generators: they are programmable, lack mechanical inertia, provide limited short-circuit contribution, and can interact in a wide range of frequencies due to their embedded wideband control structures. Consequently, the power system is shifting from a high-inertia, slow-transient-based system to a highly dynamic and variable one [1]. In this context, operators are seeking innovative tools to maximize their network resilience and real-time performance during the energy transition period, recognizing that certain traditional tools will become progressively less useful or outdated [2]. For example, operators are increasingly shifting power network studies from Phasor-based simulations to Electromagnetic Transient (EMT) simulations, given the latter's capacity to capture with high fidelity the dynamics of modern power systems [3].

In this context, the concept of the Digital Twin (DT) has gained significant attention over the years [4]. While various definitions exist, a common understanding is that a DT involves a bi-directional communication between a physical object and its digital counterpart, enabling full integration and continuous synchronization between the two. This bi-directionality is what uniquely distinguishes DTs. The concept has been widely adopted across industries, with virtually every large-scale manufacturer implementing some form of DT in the past decade. In the power and energy sector, several companies have integrated DTs into their operations [5]. However, most existing DT applications in this sector rely on centralized computation, low-bandwidth communications, and historical data analytics, which are inadequate for capturing the fast dynamics inherent in renewable energy and power electronics-dominated networks, particularly at the device level. That being said, recent advancements in edge computing, high-bandwidth communications, and real-time data-driven analysis capabilities are being integrated into modern DT applications, significantly enhancing their ability to address the challenges posed by modern PE-dominated networks.

This article introduces the concept of a High-Performance Computing-enabled Digital Twin (HPC-DT), specifically designed to enhance the resilience and real-time performance of renewable power systems. The HPC-DT fully leverages the capabilities of High-Performance Computing (HPC) to represent large and complex power networks with the high fidelity required for analyzing and operating power electronics-dominated systems. By integrating vast amounts of data captured from power system measurements, the HPC-DT combines data-driven and physical models to provide an improved real-time assessment of the network's status. A critical aspect of this concept is the integration of HPC systems for coordinated analysis and global decision-making with distributed edge processing, enabling fast, local, and autonomous decisions. These enhanced capabilities pave the way for the development of an innovative suite of tools, further discussed in this article. It is important to note that the tools presented here are proposed to illustrate the potential of the HPC-DT system; they require further refinement, expansion, and validation before being fully deployed in modern power system operation control centers.

The article is structured as follows: Section 2 outlines the architectural framework of the HPC-DT, detailing its key parts and in Section 3 a portfolio of specialized tools to address specific challenges in power system management is presented.

2. HPC-DT architecture

This section introduces the architecture of the HPC-DT. Figure 1 presents a high-level conceptual diagram of the system, which is divided into two main components: the real power system and the Digital Twin. Within the Digital Twin, a suite of tools is available for the operator, supported by a hybrid HPC/Cloud/Edge architecture. These tools can be applied at the Edge, Server, or HPC level depending on their response time scale, input data requirements, and the distributed computing characteristics. Further details on the interactions between these components are provided in the subsequent sections.

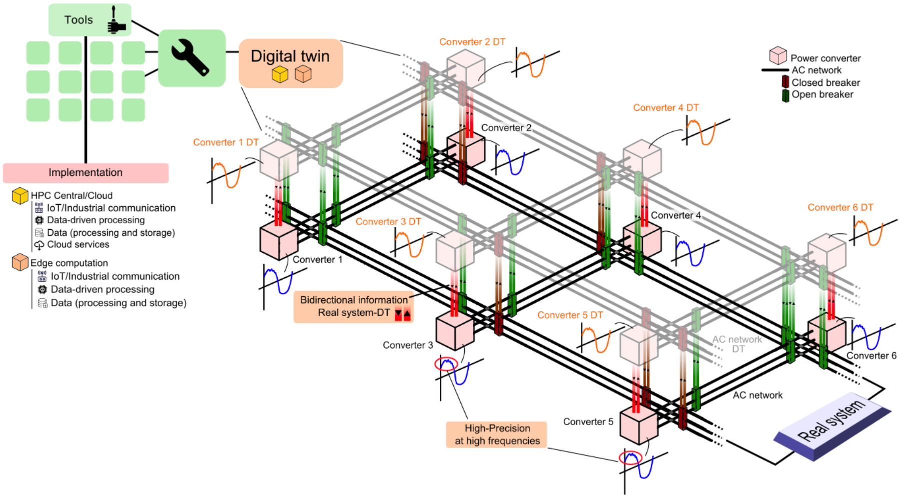

Figure 1. HPC-DT concept definition

The description of the functionality provided by the various components in the architecture is outlined according to the computing capacity of its IT elements, beginning with the resource-constrained components near the physical assets (Edge) and progressing through the Cloud or on-premise Server, where operators can manage their control systems, and ultimately leading to the extensive computing power provided by HPC systems. Three main blocks can be distinguished:

Edge computation: the edge nodes incorporate a software component which has three main purposes: interacting with the network physical elements (e.g., power converters, protections, etc.), send the state of the device to the DT, run a fast, local and autonomous control logic (e.g., AI-inference interaction detection and mitigation algorithm). In terms of implementation, these nodes could be embedded in the control systems of the physical devices.

Server: This asset gathers the information sent by the different edge nodes to present it to the system administrators to allow them to operate the network. This part also incorporates a database to capture historical data from the real network operation, which will be useful for implementing data-driven tools. In addition, the Server also allocates the different DT tools, although certain ones might be distributed across the Edge nodes. As a key particular tool, the Server incorporates the real-time network replica, where different options are considered: (1) Power flow; (2) Phasor; (3) EMT. The Server can be allocated in the Cloud or in a particular machine of the power system operator.

HPC: As a final part, some of the envisaged DT tools require a large computing power capacity that might not be present nor in the edge neither in the Server (depending on the implementation). For instance, training a data-driven model might require processing a large amount of data or the generation of new datasets to generate simple AI models to be deployed in the edge. Therefore, incorporating the access to an HPC system capable of finding the most suitable actions in the shortest time possible is a key feature of the DT. To orchestrate the tasks across the DT architecture levels the COMPS runtime [6] will be considered. COMP Superscalar (COMPSs) is a task-based programming model that allows developing and deploying applications in distributed architectures, abstracting the actual application from the underlying infrastructure. COMPSs can balance and orchestrate the load of tasks among edge nodes, cloud, and HPC, depending on the available resources at the different processing levels.

3. HPC-DT tools

The implementation of the HPC-DT includes different tools developed to maximize networks' resilience and real-time performance to be used by network operators. Each of the mentioned tools can transcend the envisaged HPC-DT application, as they could be individually implemented by network operators, provided that they have the required infrastructure in place. They have been separated in five different groups, to facilitate the description and classification.

T3.1 Online stability and interaction detection tools (Group A)
Tool A.1: Online stability assessment of power networks. This tool aims to provide real-time information on the stability of the system represented by the HPC-DT. A combination of conventional electrical engineering tools (e.g., eigenvalue analysis, participation factors, etc.), together with innovative data-driven methods, are used to provide information on the real-time stability and the margin towards instability of the system.
Tool A.2: Online interaction assessment between power system elements. This tool aims to detect real-time interactions in the system that the DT is representing. Based on the different measurements (edge) and the hybrid cyber-physical models running locally, this tool aims to first detect the interaction between system elements and possibly mitigate it acting locally.

T3.2 Real-time network performance tools (Group B)
Tool B.1: Real-time optimal operation of the network, avoiding system limitations (overload, overvoltage, etc.). This tool will run real-time Optimal Power Flows (OPF) to identify the optimal network operational state. The tool integrates dynamic stability constraints into the OPF formulation by leveraging Group A tools and data-driven techniques. These constraints are expressed as regression functions that map system stability within its operational space. The mapping is derived from offline synthetic dataset generation, after which the regression models are trained and incorporated into the OPF to account for stability limitations in static analysis. To optimize system operation fulfilling stability requirements, the optimization process and stability constraints enable adjustments to the system's operating point and modifications to PE control schemes and modes.

Tool B.2: Real-time network equivalents calculation. Builds online system equivalents at each bus of interest using real-time data such as topology and short-circuit power calculations. Equivalents can be calculated online and at each bus of the system (also with a high presence of power electronics, considering their short-circuit saturable characteristics).

T3.3 Protection with real-time measurements (Group C)
Tool C.1: Adaptive protection based on real-time measurements. Online monitoring of the short-circuit capacity (in power electronics-dominated networks) to assess if protections perform correctly when the short-circuit capacity changes. The tool is able to adapt the protection thresholds and coordination considering the real-time system topology and operative conditions.

T3.4 Probabilistic scenario generation tools (Group D)
Tool D.1: Probabilistic scenario tool. Based on the weather and additionally forecasted variables input, this tool aims to predict the state of the network in multiple time scales (+1min/ +15min / 24h, etc.) for improved decision making. Machine learning techniques are employed to select the most plausible scenarios, to reduce the number of cases to cover (especially when time is limited [1 min, 15 min]). Following this probabilistic scenario analysis, a decision/recommendation optimization-based sub-tool is developed to select the best actions for the sake of improving the network conditions (increase stability, reduce overloads, resilience increase, etc.). This tool can be blended with any of the previous ones, being an ideal complement to expand their scope.

T3.5 Autonomous real-time control tools (Group E)
Tool E.1: Real-time automatic/autonomous operation and control of power systems. This tool makes autonomous decisions acting over the real system, based on available information provided by the previous tools (Groups A-D). It provides recommendations/actions to be executed over the system and coordinates this set of actions, executing them in a secure and reliable manner. This tool is designed to close the loop between the HPC-DT and the real system,

covering the different DT layers, including communications, processes, etc., ensuring that the actions can be applied. Its adequate operation relies on the input from other tools.

The presented tools, specifically designed for operators, leverage the key features of the HPC/Edge infrastructure, and while this suite represents a strong foundational proposal, it is inherently expandable and adaptable, allowing for the integration of additional tools.

4. Summary

The HPC-DT concept is an innovative tool designed to support power system operators in managing modern power networks. By integrating HPC, Cloud, and edge processing capabilities, this hybrid approach ensures that the system effectively handles the complex and dynamic nature of today's power grid, providing operators with a new breed of tools to enhance both the resilience and real-time performance of the grid, particularly during the energy transition.

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