Upskilling Protection Engineers for the Digitalised Power System with High Fidelity Digital Twins (HFDT): A Joint Vendor–Training Institute Response to European Upskilling Reports

Ali Husain*, **Andrea Bonetti***, **Andreas Carlsson****, **Cédric Harispuru*****, **Dhanabal Mani***, **Hamdan Almukhalas***, **Niclas Wetterstrand***, **Tomas Eliasson*****

* ali.husain@megger.com, Megger, Bahrain
* andrea.bonetti@megger.com, Megger and STf, Sweden
** andreas.carlsson@stf.se, STF Ingenjörsutbildning AB, Sweden
***cedric.harispuru@siemens.com, Siemens, Germany
* dhanabal.mani@megger.com, Megger, US
* hamdan.almukhalas@megger.com, Megger, Saudi Arabia
niclas.wetterstrand@megger.com, Megger, Global
*** tomas.eliasson@kraftic.se, Siemens and STF, Sweden

Abstract

The digitalisation of power systems is transforming the skills required of protection engineers. European policy reports, echoed by similar initiatives in the United States, underline the urgency of acquiring new competencies in digital tools, virtual environments, and simulation-based training. This paper presents HFDT as a concrete response from vendors and training institutes to these identified upskilling needs. HFDT are manufacturer-authored, functionally equivalent replicas of relays and test equipment, operating in virtual time with full algorithmic fidelity. They enable training and testing that is safe, repeatable, cost-efficient, and scalable — addressing precisely the challenges outlined in the reports.

In 2025, Megger, Siemens, and STF Ingenjörsutbildning AB jointly launched professional courses using HFDT technology, first in June and again in October, demonstrating how industry and training providers can translate policy recommendations into practical, high-quality education. These initiatives illustrate a model where every trainee can work independently with their own complete setup, enhancing engagement, confidence, and competence while overcoming the hardware and safety limitations of traditional relay protection courses.

Beyond training, this paper clarifies what HFDT are, how they differ from simulations, and how they can be applied to protection testing, commissioning, and future international standardisation efforts.

Keywords: HFDT, High Fidelity Digital Twin, Upskilling, Power System Digitalisation, Virtual Relay-Testing

1. Introduction

The power system is undergoing profound change. The integration of renewable energy sources, the deployment of smart grid technologies, and the digitalisation of substations are reshaping the daily work of protection engineers. Traditional training approaches, centred on physical equipment and classroom practice, are no longer sufficient to prepare the workforce for this transformation. Engineers must acquire digital skills, learn to operate in virtual environments, and gain familiarity with new methods for testing and commissioning in a context where efficiency, safety, and scalability are critical.

This need has been clearly identified in recent policy reports. In Europe, the ETIP SNET 2025 report [1] on upskilling highlights digital competence as a decisive factor in enabling the energy transition. Similarly, in the United States, studies from DOE and EPRI [2] [3] have called for urgent workforce adaptation to meet the challenges of grid modernisation. These reports establish a consistent message across continents: upskilling for the digitalised power system is not optional but an essential precondition for success.

This paper introduces High Fidelity Digital Twins (HFDT) as a concrete response to these policy-driven demands. HFDTs are manufacturer-authored, functionally equivalent replicas of relays and test equipment, operating in virtual time with full algorithmic fidelity. Unlike simulations or simplified models, HFDTs enable engineers to test, commission, and train in a digital environment that behaves exactly as the real devices would. This capability opens the door to training formats that are safer, more scalable, and more effective than traditional hardware-based methods, while also enabling new workflows in protection testing and commissioning.

The relevance of this development extends well beyond Europe. In Saudi Arabia and the wider Middle East, large-scale programmes in renewable integration, digital substations, and grid expansion are creating similar upskilling needs. Saudi Vision 2030 emphasises human capital development and localisation of advanced engineering skills [4]. HFDT-based training offers a direct match to these objectives, providing a scalable and internationally proven model that can be adapted to regional requirements.

The aim of this paper is therefore twofold: first, to show how HFDTs directly address the upskilling needs identified in international policy reports; and second, to present the concrete vendor–training institute collaboration between Megger, Siemens, and STF Ingenjörsutbildning AB, where professional training courses using HFDTs were delivered in Sweden in 2025. Beyond training, the paper also clarifies what HFDTs are, how they differ from conventional simulations, and how they can support protection testing, commissioning, and future standardisation.

2. Policy Framework and Reports

The urgency of workforce development is not a matter of debate but of record. In Europe, the 2025 ETIP SNET Working Group 4 report on digitalisation of the electricity system is explicit:

“Upskilling needs for the energy system to support the energy transition with a focus on digital skills”.

The report stresses that “digital competence, virtual environments, and new training methods are essential to prepare the future workforce”. This statement captures three key priorities:

- The mastery of digital tools and algorithms,
- The use of virtual training platforms, and
- The deployment of innovative, scalable training methods.

Notably, the report highlights digital twins as a recognised enabling technology for this transformation. This is significant, as it shows that the concept has moved beyond academic exploration into policy endorsement: industry and governments expect digital twins to play a central role in upskilling.

In the United States, the Department of Energy (DOE) Grid Modernization Multi-Year Program Plan and the EPRI framework Workforce Skills of the Future deliver a similar message. They argue that “simulation and digital training must become part of everyday practice” to equip engineers for the modern grid.

For Saudi Arabia and the wider Middle East, these reports are not remote policy documents but relevant roadmaps. Saudi Vision 2030 places human capital development and the localisation of advanced engineering skills at the heart of its strategy. The scale of renewable integration, smart grid projects, and digital substation deployments in the Kingdom creates the same upskilling needs described in Europe and the US. By aligning with the ETIP SNET recommendations, vendors and training institutes can demonstrate that their initiatives are not only technically sound but also consistent with internationally recognised priorities.

In summary, the policy framework provides a clear demand signal:

- Challenge: upskilling engineers for the digitalised power system.
- Priority areas: digital skills, virtual environments, scalable methods.
- Response required: concrete, vendor-supported training initiatives.

The next section introduces High Fidelity Digital Twins (HFDT) as the industry’s practical response to these policy imperatives priorities.

3. HFDT – Concept and Definition

The term digital twin is increasingly used across many industries, but often without precision. In the context of protection engineering, this can create confusion between different technologies. For this reason, we introduce the term High Fidelity Digital Twin (HFDT) to describe the specific class of tools relevant for protection training and testing.

An HFDT is a manufacturer-authored, functionally equivalent replica of a physical device, such as a protection relay or a relay test set. Unlike simplified models or approximations, an HFDT executes the same algorithms as the physical device, ensuring that its behaviour in a virtual environment is identical to reality. This “high fidelity” is the defining characteristic: it is not an imitation, but a digital counterpart with full functional integrity, developed, type tested released and maintained by the same manufacturer responsible for the physical counterpart of it; its physical twin.

Definition: Virtual, in its common English meaning, refers here to something not physical but faithfully reproducing the behaviour of the real system.

HFDTs operate in virtual time, meaning that processes can be paused, rewound, or accelerated. This differentiates them from virtual IEDs (vIEDs), which are real-time software implementations designed for operational use in substations. An HFDT is not an operational device; it is a tool for training, testing, and validation in a virtual environment — that is, in a context that is not physical, but behaves exactly as the real equipment would.

Equally, HFDTs are not the same as IEC 61850 simulations, where communication-level functions described in SCL (GOOSE, SV, MMS reports etc.) can be replicated by another device, usually a computer [5]. While these mechanisms are useful for communication testing Figure 1), they do not replicate the internal protection algorithms of the device.

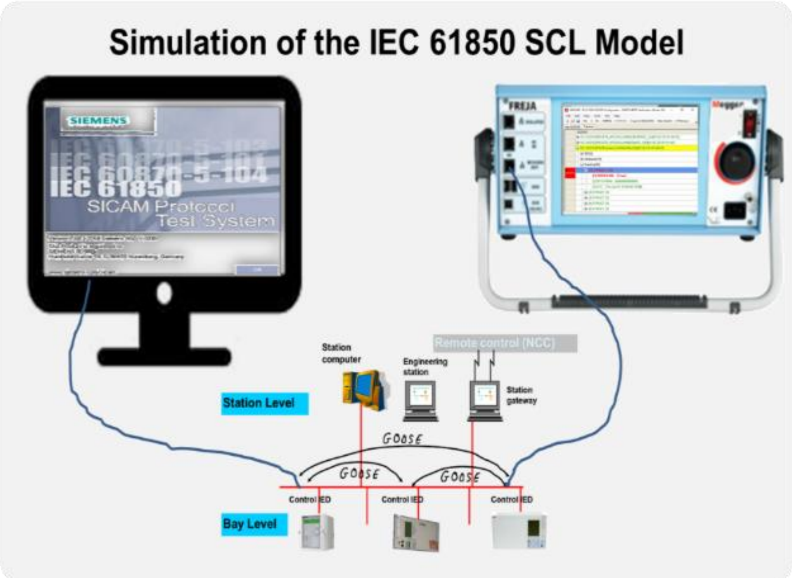

Figure 1 Simulation of IEC 61850 communication based on an SCL file.

Another source of misunderstanding from the word simulation is also related to IEC 61850, where it formally describes the "simulated SV Streams and/or GOOSE messages". The test and simulation mechanisms are well described in IEC 61850 for relay protection testing [6] , but they refer to a different type of activities (Figure 2 and Figure 3) then the ones offered by HFDT (in reality HFDTs offers the two above possibilities, and even more then them, but in a virtual environment).

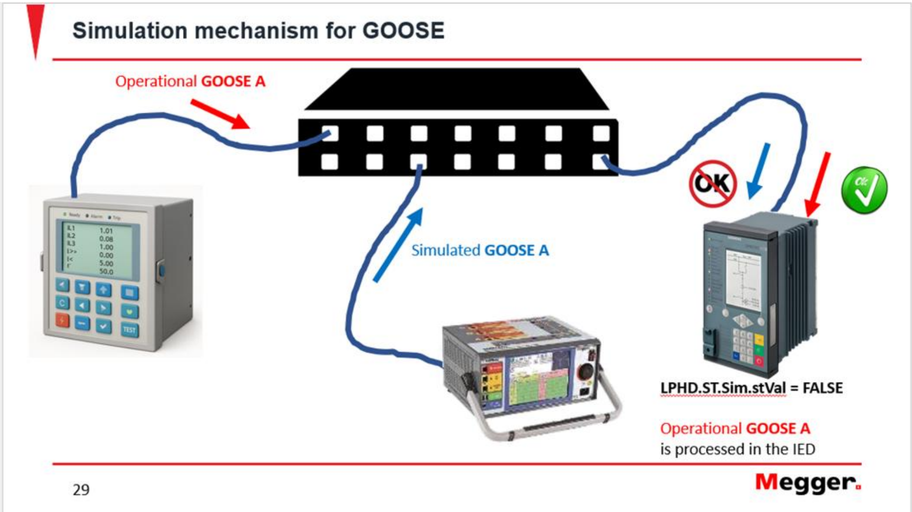

Figure 2 Simulated and operational IEC 61850 GOOSE messages.

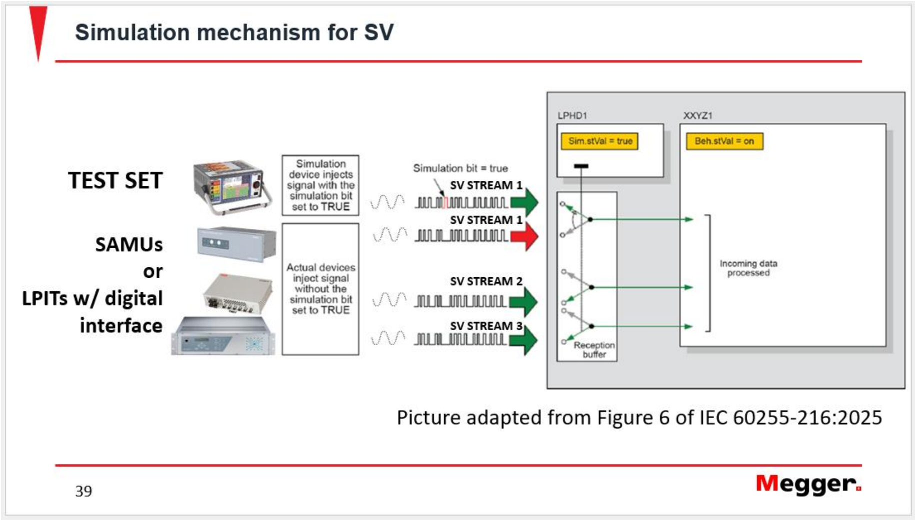

Figure 3 Simulated and operational IEC 61850 Sampled Values streams.

By contrast, an HFDT provides a complete, algorithmic copy that can be co-simulated with other HFDTs, such as a relay and a relay test set, to form a closed-loop environment when the two twins run in co-simulation [7] [8] (Figure 4).

Figure 4 Co-simulation of two HFDT with bidirectional exchange in virtual time.

Introducing the explicit term High Fidelity Digital Twin (HFDT) has two advantages. First, it prevents misunderstanding by clearly distinguishing this technology from other digital or virtual tools. Second, it lays the foundation for future standardisation, where precise terminology is essential. As has been the case with IEC 61850 communication standards, industry-wide adoption of consistent language will be key to interoperability and trust.

In this paper, HFDTs are presented not as a future concept but as real, released products already deployed in professional training. The following section explains how vendors and training institutes have used HFDTs to translate policy recommendations into practice.

4. Vendor and Training Institute Response

The policy reports calling for new digital skills and virtual training environments create a clear demand. But demand alone does not create solutions. A coordinated response from industry and training providers is necessary to transform policy recommendations into practical action.

In 2025, Megger, Siemens, and STF Ingenjörsutbildning AB joined forces to deliver such a response (Figure 5). Each organisation contributed complementary expertise:

- Siemens developed the HFDT of a protection relay (released year 2019), ensuring that trainees could interact with a device that behaved exactly like the physical equipment.
- Megger developed the HFDT of a professional protection relay test set (released year 2021), providing the virtual test environment for hands-on practice.
- STF, as an established professional training provider in Sweden, designed and delivered the course structure, integrating HFDT technology into an established educational framework (June 2025).

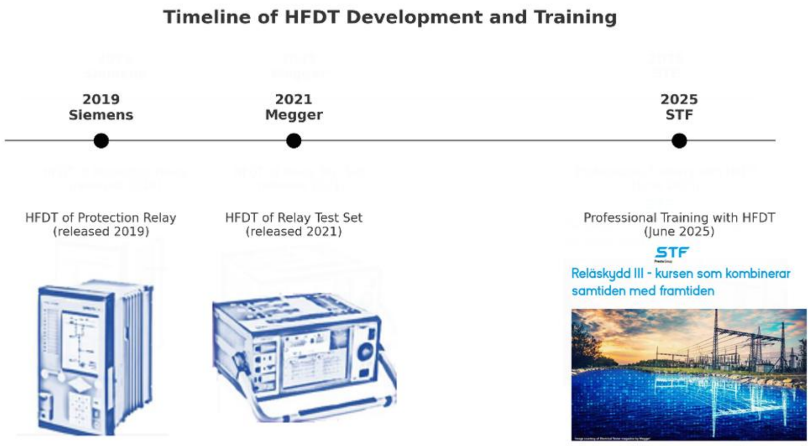

Figure 5 Timeline of HFDT development: Siemens (2019), Megger (2021), and STF training course (2025)

Together, this collaboration created a complete HFDT training ecosystem: each trainee was provided with their own digital test set and relay, forming a closed-loop system for virtual testing and commissioning exercises. This setup directly addressed the barriers that had limited traditional training:

- Hardware constraints: in conventional relay courses, expensive equipment forces students to share devices, with some participants becoming passive observers. With HFDTs, every participant has full control of their own complete setup.
- Safety concerns: HFDT training involves no high voltages or risk of damaging equipment. Students can experiment, make mistakes, and repeat exercises without fear of physical consequences.
- Logistics and costs: no shipping of test sets or relays, no export paperwork, and no customs delays. Training can be prepared and delivered across borders with minimal overhead.

By combining vendor-authored HFDTs with a professional training framework, this initiative provides a scalable model that can be repeated internationally. It represents a clear answer from vendors and training institutes to the skills gap identified in the European and US reports: a practical, cost-effective, and immediately applicable training solution for the digitalised power system.

The next section presents the first two professional courses delivered in Sweden, documenting how HFDTs have been used in practice and the feedback received from participants.

5. Case Study: STF Training Courses in Sweden, 2025

The first professional training course using HFDTs was delivered at STF Ingenjörsutbildning AB in Stockholm in June 2025 (Figure 6).

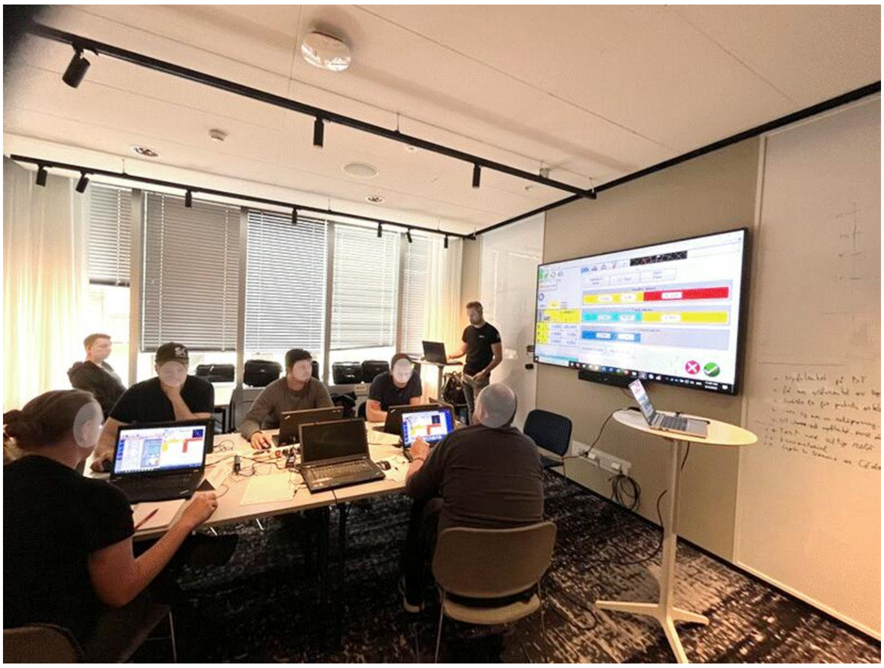

Figure 6 The first STF relay protection training with HFDT, where each participant had their own relay and test set. Image blurred for privacy. Courtesy of STF, Sweden.

The course, titled Reläskydd III – Commissioning of Protection Relays with Digital Twin Technology, marked a world-first: every participant was given a complete HFDT-based training environment, consisting of a digital relay and a digital relay test set.

5.1 Training structure

The course followed a blended structure of:

- Theoretical modules on protection commissioning, IEC testing methods, and system concepts.
- Practical HFDT sessions, where each participant performed commissioning tasks in a virtual closed-loop environment.

Unlike traditional courses, no physical relays or test sets were used during the hands-on portion. All practice was carried out exclusively in the virtual environment, giving each participant a safe, independent, and fully repeatable training setup.

5.2 Outcomes and feedback

Feedback from participants was strongly positive. The HFDT-based format changed the training dynamics in ways that surprised even the instructors.

Traditionally, relay protection courses rely on forced grouping: several participants share one physical setup, and only one or two operate the equipment while others may remain passive. It had been assumed that this grouping was a natural preference for teamwork.

However, in the June 2025 HFDT course, where every participant had their own complete setup, a different pattern emerged. Participants preferred to work individually, thinking through the steps on their own and taking full responsibility for the commissioning process. Only afterwards did they regroup for collective discussions, comparing results and analysing differences.

This shows that the earlier model of group work was not a pedagogical choice but a constraint imposed by hardware scarcity. With HFDTs, independence and responsibility became the default, and discussions became more balanced because all participants had completed the same exercises. This represents a fundamental pedagogical shift: individual responsibility first, then collaborative reflection.

5.3 Future courses

A second course is scheduled for Autumn 2025 in Stockholm, expanding on the first edition and incorporating refinements based on participant feedback. At the time of writing (September 2025), this course has not yet been delivered, but early registrations indicate strong interest.

During the June course, several participants expressed the wish to complement the HFDT-based training with a final session on physical devices, in order to apply in a real environment the same test plans and protection settings they developed virtually. This request has been taken into account by the organisers and is planned for the next version of the course in 2026, creating a hybrid model: HFDT for safe, scalable, and repeatable learning, followed by validation on real hardware.

6. Beyond Training – Wider Applications of HFDT

While the first professional applications of HFDTs have been in training, their potential extends much further. Because HFDTs reproduce the full functional behaviour of relays and test sets, they can be integrated into workflows that today require physical devices.

6.1 Virtual Testing of Protection Relays

When an HFDT relay interacts with an HFDT test set, a closed-loop virtual testing environment is created. Test plans can be developed, executed, and repeated in this environment with results identical to those obtained from physical equipment. The same test plans can later be re-used during on-site commissioning, saving time and reducing risk. This capability allows commissioning engineers to prepare in advance, ensuring efficiency and quality once on site. The first released products with HFDT allowing the virtual testing of protection relays have been documented in 2021 [9].

6.2 Virtual commissioning and system validation

HFDTs enable pre-commissioning activities to be carried out entirely in a virtual environment. Relay settings, test plans, and protection logic can be verified and validated before the physical devices are even delivered. This reduces the duration and complexity of on-site activities and helps avoid costly delays.

6.3 Remote support and troubleshooting

HFDTs provide a unique tool for remote collaboration. Engineers facing challenges in the field can share test plans and relay settings with experts working on HFDT replicas. Because the HFDT behaves exactly like the real device, troubleshooting can be performed remotely with high accuracy. This opens new possibilities for vendor support, utility operations, and cross-border knowledge transfer.

6.4 Pedagogical reinforcement

These extended applications also reinforce the training benefits. Trainees who learn on HFDTs gain direct skills that transfer into commissioning and support work. Because they have already practiced extensively in a virtual environment, they are familiar with the interface, menus, and behaviour of the devices before encountering the physical equipment.

This preparation reduces the danger of mistakes and damage in the real world. In practice, students arrive at the site already knowing how to operate the devices. Their focus can shift to the correctness of physical connections and safety procedures, while the risk of errors due to inexperience with the equipment is much lower.

As a result, HFDTs not only make training safer and more scalable, but also make real-world commissioning more secure and efficient, bridging the gap between classroom and field practice.

7. Standardisation and Future Outlook

The introduction of HFDTs into protection engineering represents not only a technological innovation but also a challenge for standardisation. For HFDTs to reach their full potential, interoperability and common understanding must be achieved across vendors, training institutes, and utilities.

7.1 The need for interoperability

Today, each HFDT is created by the original manufacturer of the physical device. This ensures full fidelity but also raises the question of how different HFDTs from different vendors can interact in larger systems. Just as IEC 61850 enabled interoperability in substation communication, a similar effort will be required for HFDTs in training and testing environments.

7.2 Ongoing standardisation efforts

Work is already in progress in several international organisations:

Work is already in progress in several international organisations:

- IEC TC 95 focuses on physical protection relays. Since an HFDT is functionally identical to its corresponding device, compliance with TC 95 standards extends

naturally to the digital twin. TC 95 therefore does not actively address HFDTs at this stage.
- IEEE PAR P3416 – Guide for Test Sets and Tools for Testing Protective Relays [10], which is under development and not yet published, already lists virtual testing among the topics in scope. This creates an opening for HFDT to be formally recognised as part of future testing frameworks.
- ISO/IEC JTC 1/SC 41 (Internet of Things and Digital Twin), which addresses digital twin definitions and frameworks across industries.
- CIGRE Study Committee D2 includes a Joint Working Group A3/D2.52 — Application of Digital Twin in Switchgear, explicitly focusing on digital twin applications in power system components [11].

These activities are at an early stage, and strong industry participation will be essential to ensure that the specific requirements of protection engineering are addressed.

7.3 Importance of Terminology

A critical step in this process is terminology. The word digital twin is used inconsistently across industries, often to describe anything from simple models to complex co-simulations. By explicitly using the term High Fidelity Digital Twin and its acronym HFDT, this paper emphasises the distinctive value of manufacturer-authored replicas with full algorithmic fidelity. Consistent use of this terminology in industry papers, training materials, and standardisation discussions will support the development of robust definitions and clear scope.

7.4 Future outlook

Looking forward, the adoption of HFDTs is expected to expand along several dimensions:

- Wider availability of HFDT relays and test sets from different vendors.
- Closed-loop testing with HFDTs becoming a standard complement to physical commissioning.
- Hybrid training formats combining HFDT-based preparation with selected physical exercises.
- International rollout, where proven models from Europe can be adapted to other regions.

For Saudi Arabia and the Middle East, this outlook is directly relevant. The region's ambitious investment in digital substations and renewable integration creates both the need and the opportunity to adopt HFDT-based training and testing early. By doing so, the region can leapfrog directly to a modern, scalable, and standardised approach, avoiding the constraints of purely hardware-based training.

8. Conclusions

The digitalisation of the power system demands a new skillset for protection engineers. Policy reports from Europe and the United States converge on the same message: the workforce must be equipped with digital skills, exposed to virtual environments, and supported by new forms of training. Without this, the energy transition will face critical bottlenecks.

This paper has shown how High Fidelity Digital Twins provide a direct and practical response to these upskilling needs. HFDTs are not simulations or simplified models, but manufacturer-authored, functionally identical replicas of protection relays and test equipment. By operating in virtual environments, HFDTs enable training, testing, and commissioning that are safe, repeatable, and scalable.

The first professional HFDT-based training course, delivered by STF Ingenjörsutbildning AB in June 2025 in collaboration with Megger and Siemens, demonstrated the value of this approach in practice. Every participant worked independently with a complete HFDT setup, leading to a shift from forced group learning to individual responsibility, followed by richer collective discussions. The overwhelmingly positive feedback, and the request to complement the HFDT training with a physical session in future iterations, underline both the effectiveness and the acceptance of this model.

Beyond training, HFDTs extend naturally into commissioning preparation, closed-loop relay protection testing, and remote support. Their adoption will reshape workflows and increase efficiency across the lifecycle of protection engineering tasks. For this promise to be fully realised, standardisation and consistent terminology are essential. The explicit use of the term High Fidelity Digital Twin is a step in this direction, distinguishing these tools from other virtual or simulated environments.

For Saudi Arabia and the Middle East, the timing is particularly relevant. The region's ambitious programmes for renewable integration and digital substations create an immediate need for scalable training and advanced testing tools. By adopting HFDTs, the region can leapfrog to a modern, internationally aligned solution that directly supports its human capital development goals under Vision 2030.

In conclusion, HFDTs are no longer a research concept but a proven reality. They represent the vendors' and training institutes' concrete answer to the upskilling needs identified in international policy reports, and they hold the potential to become a global standard for how protection engineers are trained and supported in the digitalised power system.

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