A Real-Time EMT Digital Model for a Dutch Regional EHV Network: Integrating Offshore Power

Jonathan Aviles-Cedeno
Intelligent Electrical Power Grids
Delft University of Technology
Delft, The Netherlands
J.A.AvilesCedeno@tudelft.nl
ORCID: 0000-0002-3386-0643

Jose Rueda
Intelligent Electrical Power Grids
Delft University of Technology
Delft, The Netherlands
J.L.RuedaTorres@tudelft.nl
ORCID: 0000-0001-7288-0228

Arcadio Perilla, Peter Palensky
Intelligent Electrical Power Grids
Delft University of Technology
Delft, The Netherlands
arcadio.perilla@neom.com, P.Palensky@tudelft.nl

IECON 2024 - 50th Annual Conference of the IEEE Industrial Electronics Society | 978-1-6654-6454-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/IECON55916.2024.10905203

***Abstract*—As electrical systems become increasingly complex with the integration of new electronic loads and variable renewable energy sources (VRES), modern tools are essential for their effective management and operation. This paper discusses an initial step toward the complete implementation of a digital twin for the Dutch electrical power grid: the development of a real-time digital model. This model represents the Randstad region's electrical grid, which has recently been enhanced by substantial offshore wind power installations, including Hollandse Kust Zuid and Hollandse Kust Noord.**

The Real-Time Electromagnetic Transient (EMT) model described in this study enables the assessment of the impacts of offshore wind integration on network stability and power quality. Network elements have been modeled using RSCAD and implemented within the Real-Time Digital Simulator (RTDS). Detailed simulations are conducted to evaluate the grid's capacity to handle the active and reactive power influx from the offshore wind farms. This study highlights the critical role of precise modeling in ensuring the reliability and efficiency of wind power integration into the national grid.

***Index Terms*—Digital model, digital twin, power system, power system dynamics, power flow, offshore wind farms, real-time, EMT model.**

I. INTRODUCTION

The fast evolution of electrical power systems, fueled by technological advances and the shift toward sustainable energy, presents challenges in grid management. As variable renewable energy sources (VRES) such as offshore wind farms increasingly integrate into national grids, advanced management tools are necessary to maintain reliability and stability [1].

In recent years, various models have been developed to simulate the Dutch electrical network, such as [2], which employs offline simulations. However, these models do not offer real-time analysis capabilities, limiting their use for dynamic system monitoring and control. Offline models, while useful for planning and scenario analysis, are insufficient when immediate system response is necessary.

Digital twins have emerged as a pivotal solution in this landscape. They enable real-time monitoring, simulation, and analytical processes that provide essential insights, facilitating informed decision-making and necessary operational modifications [3]–[5]. Power system operators are strongly considering the use cases of these tools in operation, stability control, and cybersecurity management [6].

To make this exchange of information in real time, the digital models shall also be real-time. Furthermore, if the digital representation will be used for stability analyses, an Electromagnetic Transient (EMT) model is required.

This study aims to create an EMT digital model of an electrical grid that includes the Randstad region of the Netherlands. As a critical hub within the Netherlands, the Randstad region has seen significant enhancements to its grid infrastructure, which is gradually transitioning towards VRES to reduce carbon emissions. The recent integration of the Hollandse Kust Zuid and Hollandse Kust Noord offshore wind farms marks a significant step forward in this regard [7].

The remainder of the paper is organized as follows. Section II analyzes available digital representations for physical systems. Section III delves into the methodology to select and configure the different components and interconnections. Section IV outlines the simulation results using the Real-Time Digital Simulator (RTDS). Section V evaluates the results and provides insight into the effectiveness of the proposed model. Finally, Section VI describes future research and developments required to achieve a complete digital twin of the electrical system of the Netherlands.

II. REAL-TIME DIGITAL MODELS: STEPPING STONES TO DIGITAL TWINS IN POWER SYSTEMS

As mentioned in [8], differentiating between various digital representations of physical systems is crucial to avoid misconceptions. The current literature offers multiple classification methods for these representations, but the classification based on the nature of data interaction between the digital and physical counterparts is particularly compelling.

This approach includes three central digital representations with characteristics detailed below.

- *Digital model* – A digital version of a physical object. In power system engineering and research, these models are utilized for simulations that can be real-time or non-real-time, supporting studies, planning, and optimization tasks.

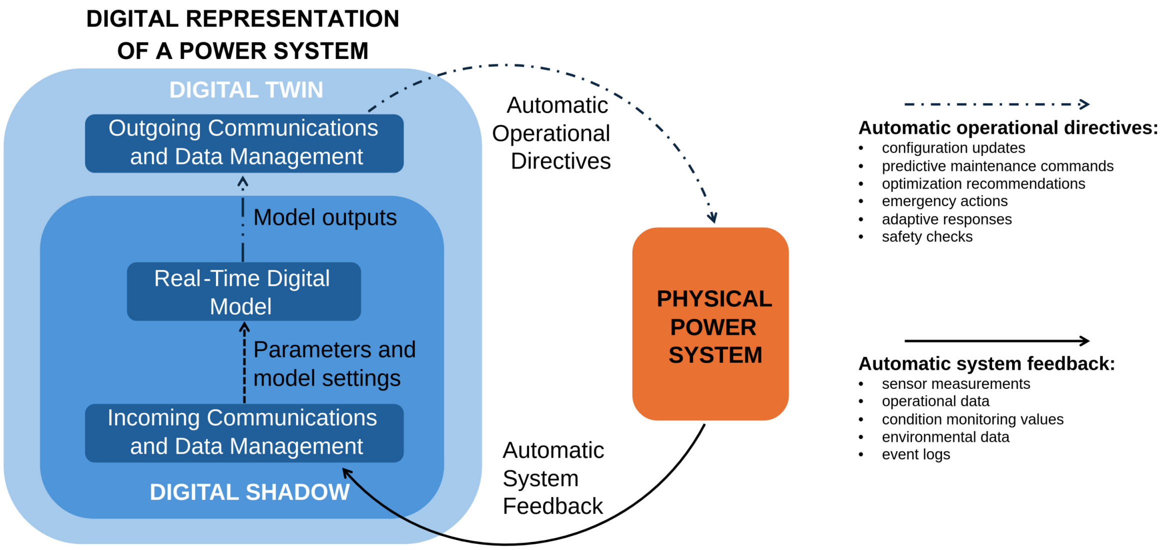

Fig. 1. Schematic representation of the digital twin of a power system and its interactions.

- *Digital shadow* – A digital representation that maintains a one-way data flow from the physical object to the digital counterpart. Updates in the physical object's state are automatically reflected in the digital shadow, enabling it to perform all tasks achievable by digital models, with the added capability of updated data usage for enhanced monitoring and operational management. Models within the shadow should be real-time or updated as rapidly as necessary for their intended tasks.
- *Digital twin* – This representation features a bidirectional automatic data flow, ensuring that any changes in one are immediately mirrored in the other. Digital twins support all functions of models and shadows and are particularly valuable for control operations and advanced system studies, with enhanced real-time responses and in-depth analysis. Models within digital twins should also be real-time or nearly real-time, depending on their task requirements.

A critical factor to consider in digital representations is the step time used by the digital models within the core of the replicas. Some applications, such as transient stability analysis, require smaller time steps due to their sensitivity to rapid changes. In contrast, other studies, like long-term system planning, may tolerate longer step times. A practical replica only requires a data exchange rate that matches the demands of the specific problem being addressed.

Fig. 1 depicts a scheme of the interactions between a digital twin and its physical counterpart. As observed, a digital twin can be modeled as the combination of a digital shadow and the necessary infrastructure to process output data and manage outgoing communications towards the physical system. Similarly, a digital shadow can be considered a combination of a real-time digital model and the required infrastructure to process input data and manage incoming communications from the physical power system.

Based on this layered building, it is easy to understand how the progression from models to shadows to twins represents an evolutionary path in how data and simulations are used to enhance understanding, monitoring, and management of power system operations.

III. REAL-TIME EMT DIGITAL MODEL DEVELOPMENT IN RSCAD

A. *Real-Time Simulation Performance*

This study conducted real-time simulations using three NovaCor racks within the RTDS system at Delft University of Technology. The model operates continuously in real-time, with a consistent simulation time step of $50\,\mu$s for the main network and a time step ranging from $1.4\,\mu$s to $2.5\,\mu$s for high-frequency components. The system demonstrated stable performance throughout, maintaining real-time operation without latency or delays.

The NovaCor racks efficiently managed the computational demands of the simulation, ensuring accurate and reliable real-time performance. This stability is essential for detailed analysis and control in complex scenarios, such as integrating offshore wind power into the Dutch EHV network.

B. *Randstad's EHV Grid*

The first step in building the extra-high-voltage (EHV) transmission network corresponding to the Randstad region was establishing its corresponding topology. Publicly available data from [9] was utilized. The transmission lines and power transformer parameters were sourced from previous research conducted at Delft University of Technology, as referenced in [10]. Additional grid data was obtained from other public data sources such as [11], an independent website focusing on the high-voltage grid in the Netherlands and Belgium. Fig. 2 shows the Randstad electrical grid and the offshore wind farms considered for the model.

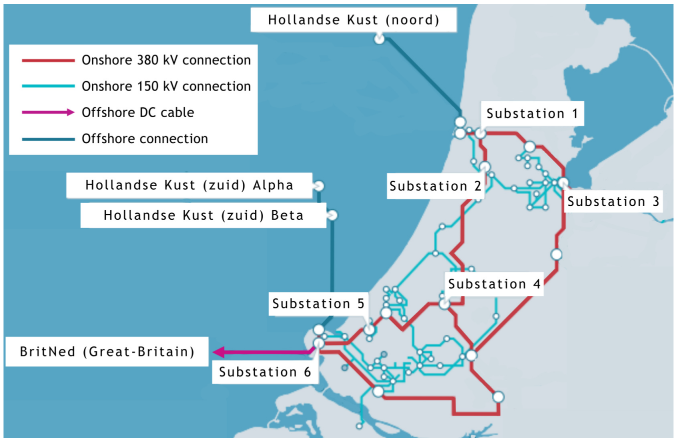

Fig. 2. Randstad region's electrical network. Adapted from [9], [12].

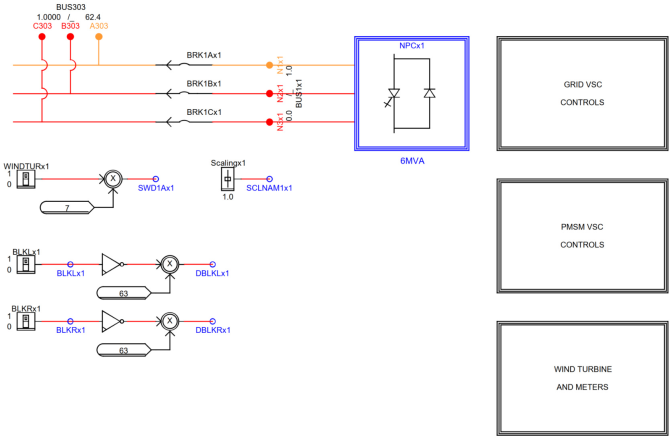

Fig. 3. Power and control connections of a wind farm in RSCAD.

C. Power and Control Connections of a Wind Turbine in RSCAD

Wind farms' power outputs were supported by data from the Netherlands Enterprise Agency (RVO) [7]. The synthetic models of the wind turbine and power converter used in the RSCAD EMT simulation were developed for the MIGRATE project [13]. This model includes a 6-MW type-4 wind turbine and its power electronic converters. The model is scaled up to 700 MW, to match the power output of Hollandse Kust (noord), Hollandse Kust (zuid) Alpha, and Hollandse Kust (zuid) Beta wind farms. Fig. 3 illustrates the components of the wind farm model, comprising:

- *Small dt Block (6 MVA)*: This smaller time-step block contains a permanent magnet synchronous machine (PMSM), voltage source converters (VSC), and the DC link between the converters.
- *Grid VSC Controls*: This hierarchy box manages the controls for the grid-side converter.
- *PMSM VSC Controls*: This hierarchy box governs the machine-side converter.
- *Wind turbine and measuring devices*: A hierarchy box that includes measuring devices and functional blocks to simulate the dynamic behavior of the wind turbine.

Each component will be examined in further detail in the subsequent sections.

D. Small Time-Step Block (Small dt Block)

Simulations run in the Real Time Digital Simulator (RTDS) via RSCAD require high-power processing to achieve real-time performance. To optimize processing demands, RSCAD allows the adjustment of simulation step times based on the specific requirements of different components. A dedicated step-time of $50\,\mu$s is established for the main network operations to balance performance and computational load.

However, power electronics components involve complexities requiring a finer time resolution for accurate simulation. The small time-step block addresses this by allowing a reduced step-time, ranging from $1.4\,\mu$s to $2.5\,\mu$s, thereby ensuring numerical stability.

Fig. 4 shows the configuration within this block. It includes a PMSM connected through a three-level voltage source converter to a DC link. The other end of the DC link is connected with another three-level converter linked to a transformer, which acts as the interface between the small step-time subnetwork (small *dt* block) and the main network.

This section also hosts triangular wave generators and firing pulse generators for the operation of the three-level converters. These components utilize a comparison method where sinusoidal waves, generated from either the grid side or the PMSM, are compared with a triangular signal. This comparison generates the necessary logic to trigger accurately the converter valves.

E. Grid VSC Controls

This hierarchy box contains the controls of the machine-side VSC, which also allows the wind turbine to recover after a fault occurs. A synchronous reference frame control or *dq*-control is used to provide adequate inputs to the controllers.

A phase-locked loop (PLL) will set the q-axis to zero. Then, this block's output angle will be used to calculate the *dq* components via the Park transformation. This transformation will be performed for the grid voltages as well as for the currents.

The PLL outputs are also used to create the shape of the triangular wave and its rate, which, in this case, is 19 times higher than the power system frequency.

Direct- and quadrature-voltage components are converted to the *abc* frame. Then, they are used to build the sinusoidal waves to compare with the triangular wave and give the firing logic for the valves on the grid side of the three-level converter.

F. Permanent Magnet Synchronous Machine (PMSM) VSC Controls

On the machine side, the currents that need to be controlled are the stator currents. As illustrated in Fig. 5, these currents are transformed into the *dq* reference frame using the rotor angle in the Park transformation. After transformation, the

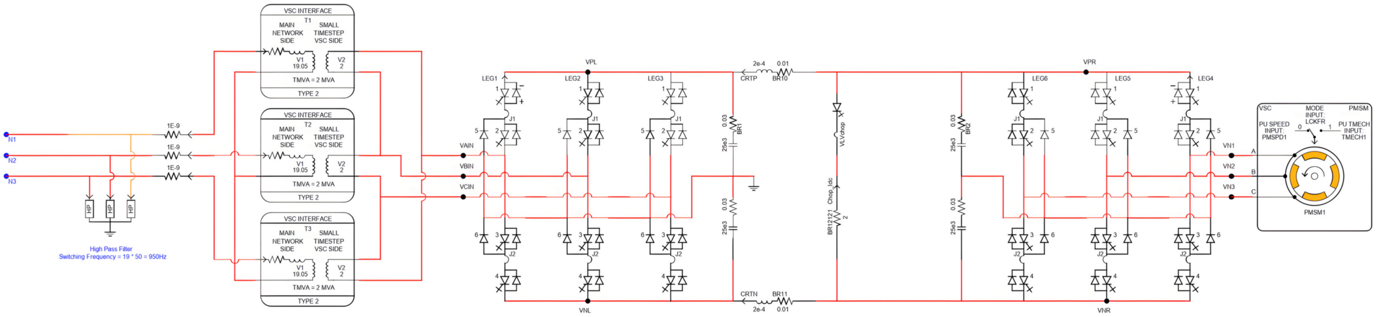

Fig. 4. Small time-step block (small *dt* block).

direct current i_d is compared with the machine speed and then introduced into the current controller. i_q is then compared to a reference current derived from a proportional-integrative (PI) controller within the maximum power point tracking (MPPT) module, optimizing power generation across varying wind speeds.

The adjusted current is fed into the current controller, whose output comprises voltages in the *dq* reference frame. Subsequently, these voltages are converted to the *abc* reference frame to generate sinusoidal waves. These waves are then compared with a triangular wave to establish the firing logic for the valves on the synchronous machine side.

G. Wind Turbine and Measuring Devices

This hierarchy box encompasses the aerodynamic model of the wind turbine, as depicted in Fig. 6. Central to this model is the power coefficient (C_p) vs. tip-speed ratio (λ) curve, which illustrates how efficiently the turbine converts wind kinetic energy into electrical power across different blade speeds. Additionally, the model integrates a control mechanism for adjusting the pitch angle, which is regulated by a slider that modifies the PMSM speed to optimize the turbine's response to changing wind conditions.

H. Equivalent Models of Neighbouring Networks

Since only the electrical network of the Randstad region is under study, connections to neighboring networks are modeled based on their active and reactive power flow extraction. These equivalents are depicted using dynamic load blocks with active and reactive power consumption equal to the corresponding power flow through the network interconnection.

IV. SIMULATION RESULTS USING THE REAL TIME DIGITAL SIMULATOR (RTDS)

A. Signal Selection

To effectively test the system's behavior, the following signals were selected:

1) Active power from three generators connected at Substation 6.
2) Active and reactive power from the Hollandse Kust Noord and Zuid wind farms.
3) Active power of the BritNed DC link.

B. Steady-State Simulation

Fig. 7 illustrates the active power response of the generators connected to Substation 6. The generators reach a steady state within 6 seconds.

Figure 8 depicts the response of the wind farms and the BritNed DC connection. The three wind farms achieve a steady-state power output of 700 MW approximately 15 seconds after initialization. The reactive power of these farms remains stable at around zero, indicating no significant fluctuations. Additionally, the BritNed DC connection attains its nominal active power in about 6 seconds and maintains it throughout the simulation.

C. Behavior under Three-Phase Short-Circuit Fault

The system resilience was tested by introducing a $150ms$ three-phase short-circuit fault at the main busbar of Substation 1, near the connection point of Hollandse Kust Noord. Exceptional settings were used as an exercise to see how unprecedented oscillations could theoretically be caused. Hence, duration of this disturbance is longer than typical real-world clearance times and it was chosen to assess the system dynamics under unprecedented challenging conditions.

Figure 9 shows the active power of the generators, which oscillates after the fault but stabilizes once the fault is cleared. In practice, faster fault clearance would likely result in less pronounced oscillations.

Figure 10 illustrates the performance of the northern wind farm. During the fault, there is a noticeable drop in active power, which stabilizes post-fault. Reactive power is employed during the fault to support voltage levels and returns to zero after the fault is cleared. The fault did not significantly affect the southern wind farms, which maintained a steady-state active power of 700 MW. Therefore, to see the response of these wind farms, a second place was chosen to apply the fault.

The second fault was applied at Substation 6's main busbar to evaluate the Hollandse Kust Zuid connection. As seen in Figure 11, the wind farms' active and reactive power show significant oscillations, which do not stabilize. In reality, coordinated control between synchronous generators and wind farms and faster protection schemes would mitigate such issues.

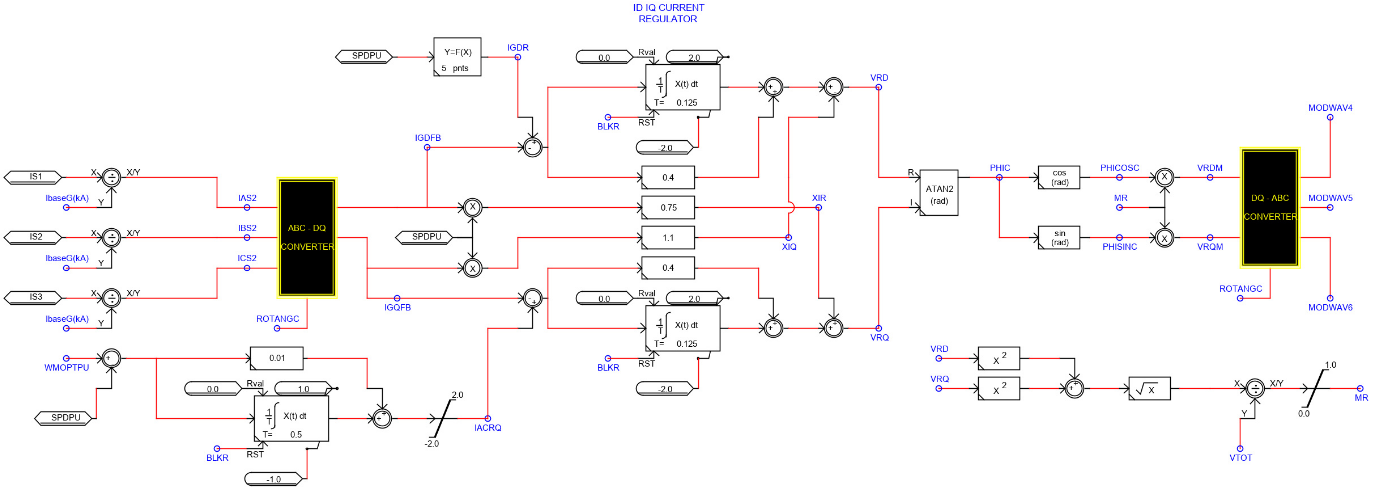

Fig. 5. PMSM current controller.

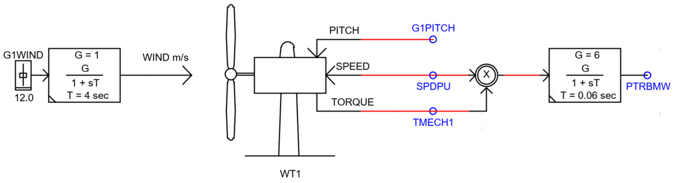

Fig. 6. Wind turbine aerodynamic model

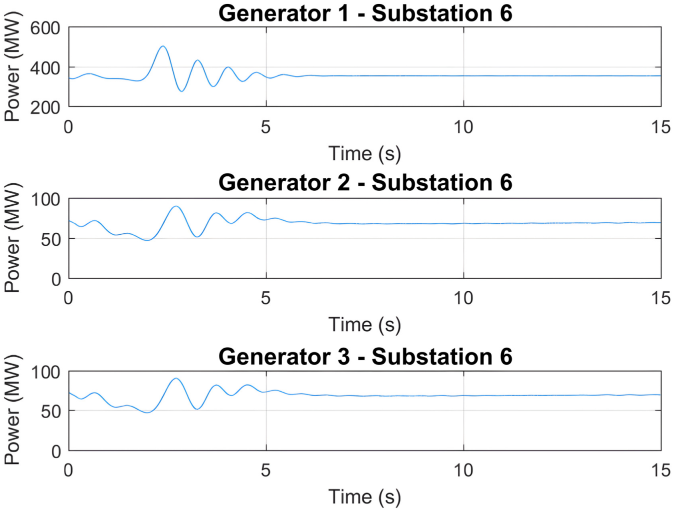

Fig. 7. Power output of generators connected to Substation 6 during normal start-up to reach steady-state in RSCAD.

V. CONCLUSIONS

This study overviews the initial development and implementation of a real-time EMT synthetic digital model designed for the Randstad region of the Dutch EHV network. Exceptional settings were used as an exercise to see how unprecedented conditions (e.g., excitation of oscillatory phenomenon) could theoretically be caused. Numerical results show the feasibility of evaluating the impact (i.e., steady-sate and dynamic system performances) of topological changes, e.g. integration of offshore wind power plants.

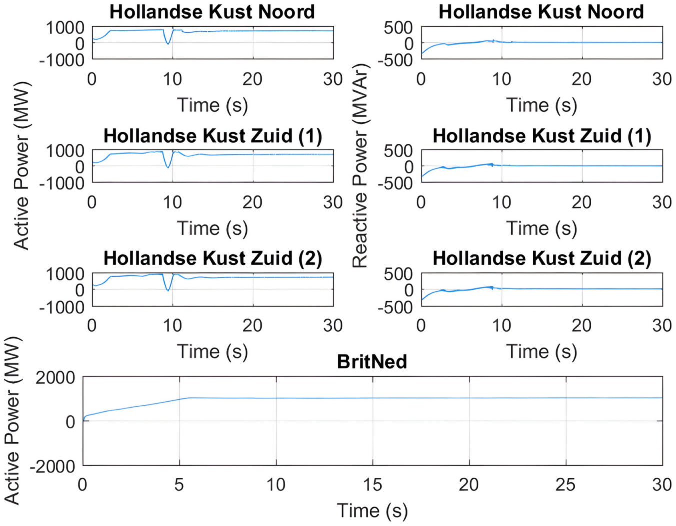

Fig. 8. Power output of Hollandse Kust wind farms (1-Alpha and 2-Beta) and BritNed during normal start-up to reach steady-state in RSCAD.

VI. FUTURE RESEARCH AND DEVELOPMENT

A primary challenge is addressing the computational complexity of a larger network size (e.g., additional renewable sources). Testing the model with real-world data is another important step. Developing a user-friendly interface will enhance practical applications by enabling real-time monitoring and control.

The digital model can be enhanced with real-time incoming communications from the physical system. and outgoing communication capabilities to enable closed loop control.

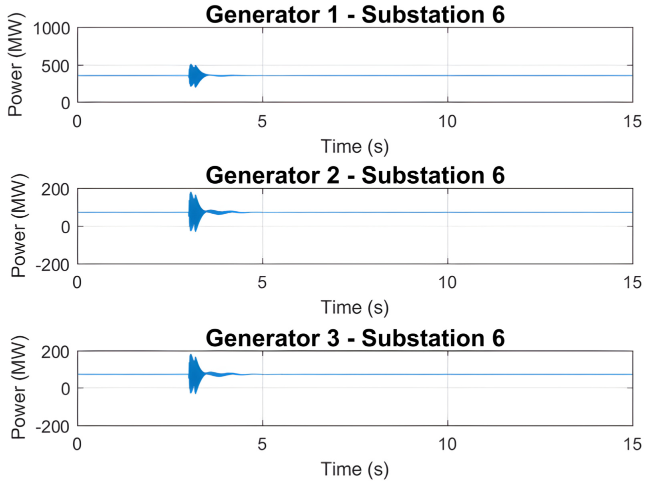

Fig. 9. Behavior of generators connected to Substation 6. Short-circuit fault.

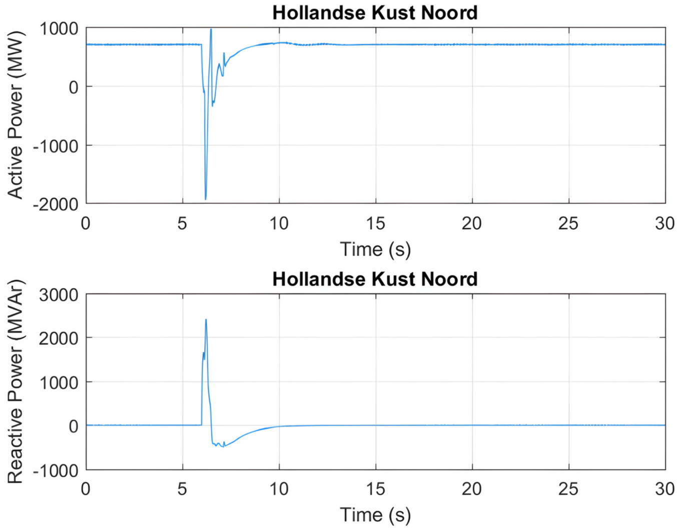

Fig. 10. Behaviour of Hollandse Kust Noord wind farm. Short-circuit fault.

ACKNOWLEDGMENT

This paper has been inspired by the outcomes of Armando Torres' master's thesis [14]. The research work shown in this paper has received funding from TenneT TSO B.V within the research project on Adaptive fast active power control for stabilization of multi-converter dynamics in offshore electrical energy-hydrogen hubs - FUTURE SYSTEM. It reflects only the authors views, and the aforesaid organization is not responsible for any use that may be made of the paper's content.

REFERENCES

[1] M. S. Alvarez-Alvarado, C. Apolo-Tinoco, M. J. Ramirez-Prado, F. E. Alban-Chacón, N. Pico, J. Aviles-Cedeno, A. A. Recalde, F. Moncayo-Rea, W. Velasquez, and J. Rengifo, "Cyber-physical power systems: A comprehensive review about technologies drivers, standards, and future perspectives," *Computers and Electrical Engineering*, vol. 116, p. 109149, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0045790624000776

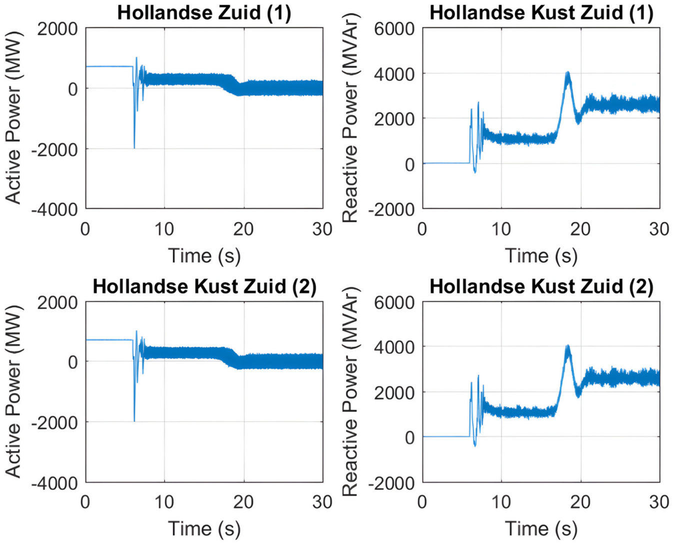

Fig. 11. Behavior of Hollandse Kust wind farms (1-Alpha and 2-Beta). Short-circuit fault.

[2] F. Reis, J. R. Torres, P. Palensky, and F. Gonzalez-Longatt, "Future dutch electricity grid: Assessing the potential of overplanting in photovoltaic systems," in *IECON 2023- 49th Annual Conference of the IEEE Industrial Electronics Society*, 2023, pp. 1–7.

[3] G. Mylonas, A. Kalogeras, G. Kalogeras, C. Anagnostopoulos, C. Alexakos, and L. Muñoz, "Digital Twins From Smart Manufacturing to Smart Cities: A Survey," *IEEE Access*, vol. 9, pp. 143 222–143 249, 2021.

[4] J. Wu, Y. Yang, X. Cheng, H. Zuo, and Z. Cheng, "The Development of Digital Twin Technology Review," in *2020 Chinese Automation Congress (CAC)*, 2020, pp. 4901–4906.

[5] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, "Digital Twin in Industry: State-of-the-Art," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 4, pp. 2405–2415, 2019.

[6] C. Brosinsky, M. Naglič, S. Lehnhoff, R. Krebs, and D. Westermann, "A Fortunate Decision That You Can Trust: Digital Twins as Enablers for the Next Generation of Energy Management Systems and Sophisticated Operator Assistance Systems," *IEEE Power and Energy Magazine*, vol. 22, no. 1, pp. 24–34, 2024.

[7] Rijksdienst voor Ondernemend Nederland (RVO), "Offshore Wind Energy," https://offshorewind.rvo.nl, 2024, accessed on 2024-05-13.

[8] A. Fuller, Z. Fan, C. Day, and C. Barlow, "Digital Twin: Enabling Technologies, Challenges and Open Research," *IEEE Access*, vol. 8, pp. 108 952–108 971, 2020.

[9] TenneT, "TenneT: Leading European Grid Operator," https://www.tennet.eu, 2024, accessed on 2024-05-13.

[10] A. de Roos, "Synthetic Steady-State Model of the Dutch EHV Network: Study of the Impact of Future Additions of VRES and Electrolysers," Master's thesis, Delft University of Technology, Delft, The Netherlands, 2021, available at: http://resolver.tudelft.nl/uuid:0ba09fe3-a9dd-4105-83c8-b0cba5bf4012.

[11] "HoogspanningsNet," https://www.hoogspanningsnet.com/, accessed on 2024-05-13.

[12] Tennet, "Onshore Projects in the Netherlands, December 2023," https://tennet-drupal.s3.eu-central-1.amazonaws.com/default/2024-02/GB_DEC2023_Onshore_Netherlands.pdf, 2024, accessed on 2024-05-13.

[13] MIGRATE Consortium, "MIGRATE Project: Massive InteGRATion of power Electronic devices," Horizon 2020 research and innovation programme, European Commission, 2023, available: https://cordis.europa.eu/project/id/691800.

[14] A. Torres, "A Singular-Value-Decomposition-Based Method For Impact Assessment Of Power Electronic Interfaced Generation On The Harmonic Response In Electrical Power Systems," Master's thesis, Delft University of Technology, Delft, The Netherlands, 2019, available at: http://resolver.tudelft.nl/uuid:57d95189-9f60-4ed5-89f7-a2aaba6f6819.