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Real-Time Simulator Study of the n-Grid Ancillary Service Product Delivery Impact on the Electric Grid

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***Abstract*—Nano-Grid (n-Grid), a customer owned distributed energy resource (DER) consisting of PV panels, and fixed and/or mobile battery storage, brings about significant benefits to power grids: carbon footprint reduction, system resilience and flexibility enhancement, and more smart grid technology innovations. A cluster of n-Grids can participate in wholesale markets through aggregation to procure ancillary service products (ASPs), which needs to meet the constraints of the underlying distribution grid (voltage, line capacity, etc.). A testbed that emulates the interaction of the n-Grids and distribution grid enables study of such impacts. We first elaborate on the cyber-physical testbed that we developed using RTDS and Typhoon-HIL real-time simulators. Then, we run certain n-Grid ASP delivery scenarios and analyze their effects on the distribution grid technical constraints. This testbed study enables a better understanding of the DER flexibility in ASP delivery and examines impacts on the power grid.**

Keywords— aggregator, cyber-physical interdependence, nano-Grid, real-time simulator, testbed

I. INTRODUCTION

The need of modern power systems for higher reliability and lower carbon footprint has led to an increasing deployment of distributed energy resources (DERs) [1], [2]. A particular type of DER that can be widely implemented in residential and commercial areas is a nano-Gird (n-Grid). It is comprised of rooftop photovoltaic (PV) panels, a fixed battery energy storage system (BESS), uni- or bi-directional electric vehicle (EV) charger(s), and controllable and non-controllable electric loads [3]-[5]. The flexibility of n-Grids, coming from the controllability of their energy resources, can be harnessed to procure ancillary service products (ASPs) to the wholesale electricity market (WEM) [6]-[8]. The n-Grid owner can benefit from this extra source of profitability and the independent system operator (ISO) can benefit from additional flexibility and reliability attained from customer-owned ASP delivery resources [9], [10]. The n-Grid market participation requires an aggregator, a third-party entity, to aggregate a cluster of n-Grids and offer ASPs to the market on their behalf [11]-[13]. The aggregator receives dispatch commands from the ISO, and sends resource management signals to n-Grids. The distribution grid interface is the physical means for ASP delivery by n-Grids. The technical constraints of the distribution grid (e.g., voltage and line capacity) must be considered for ASP delivery since otherwise the aggregator may be penalized for violating the ASP delivery constraints. [14]. The development of real-time simulators provides us with powerful tools to run realistic use cases and analyze the impact of n-Grid resources on the power grid before their large-scale implementation in residential and commercial buildings [15].

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Real-time simulators were utilized by other researchers for different use cases [15]-[19]. A real-time simulation model for wind power plants in the Hydro-Quebec electricity grid presented in [16] demonstrates the feasibility of large-scale electromagnetic transient analysis. The testing of FACTS controllers using real-time simulators is discussed in [17]. In [18], the authors tested a control mechanism to capture maximum wind power by using the concept of Hardware-in-the-Loop. A comprehensive review on different applications of the real-time simulators is provided in [19].

Our contributions in this paper are: a) Implementing a five-layer cyber-physical interdependence architecture for the n-Grid/aggregator model, b) Utilizing the testbed capability using the Typhoon-HIL and RTDS real-time simulators for understanding harnessing of the n-Grid flexibility for grid support., and c) Evaluating several use cases to analyze the impacts of ASP delivery by n-Grids on the underlying distribution grid.

II. CYBER-PHYSICAL ARCHITECTURE OF N-GRID/AGGREGATOR MODEL

Fig. 1. Shows a typical n-Grid communicating with the aggregator for ASP procurement in the WEM. The five-layer

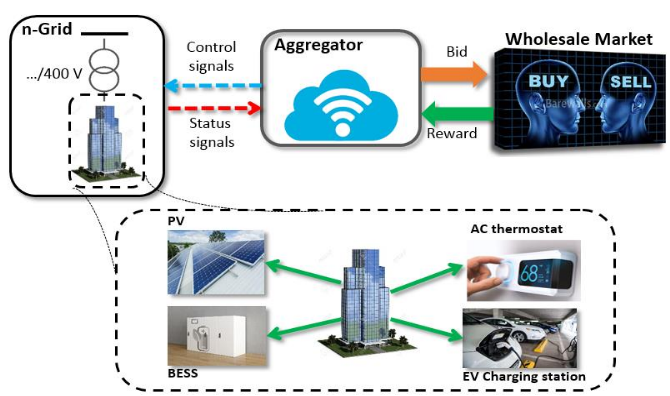

Fig. 1 The n-Grid/Aggregator participation in the WEM for ASP delivery.

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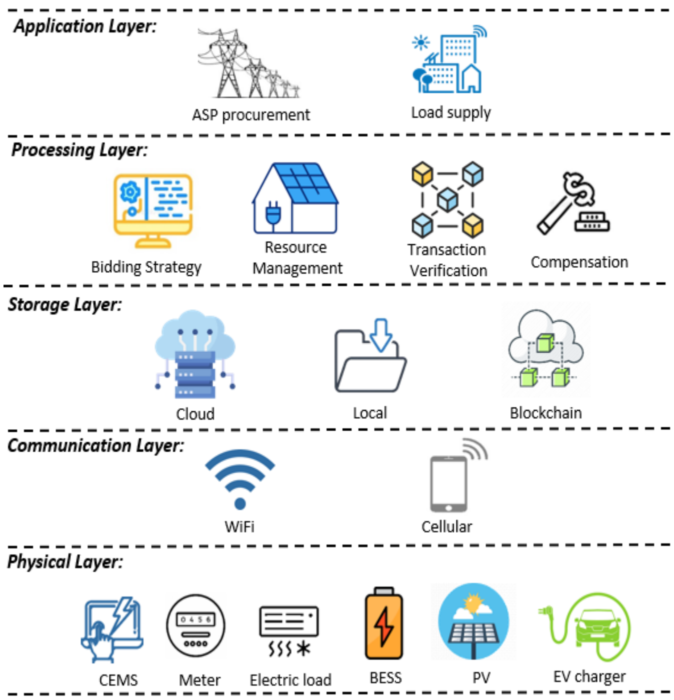


Fig. 2 The five-layer cyber-physical architecture of the n-Grid/aggregator communication model.

cyber-physical interdependence architecture for the n-Grid/Aggregator communication model is depicted in Fig. 2. The layers in this architecture with n-Grid interaction are explained below [20].

1) Physical layer: This layer consists of the physical components of the n-Grid used for power generation, consumption and storage, measurement devices, sensors and meters, and the customer energy management system (CEMS).

2) Communication layer: The Internet-of-Things (IoT) enables the communication between the n-Grids and the aggregator. Different networking protocols may be utilized for data exchange including WiFi/Ethernet for communications within the n-Grid, and 4G/LTE/5G technologies for communication with the aggregator. The networking protocols have different characteristics in terms of reliability, rate, bandwidth, security, etc.

3) Storage layer: The data received at the aggregator data center from the ISO and n-Grid, can be stored in local or cloud server. Local storage may be more reliable whereas cloud storage is easier to access and share.

4) Processing layer: The data processing is conducted in this layer. It includes the algorithms the aggregator runs for the optimal bidding strategy in the market, n-Grid resource management for ASP delivery, n-Grid resource management during outages, energy/monetary transaction verification by the ISO via the blockchain technology, and n-Grid compensation rate for ASP procurement.

5) Application layer: This layer denotes the applications and use cases of the framework. In our case, the n-Grid/aggregator communications can be used for applications such as grid support, n-Grid load supply during outages, and ASP procurement for the WEM.

III. Texas A&M Testbed

A. Testbed Details

In our testbed, we developed the n-Grid controller model in the Typhoon-HIL and the distribution grid model in the RTDS, respectively [21], [22]. As shown in Fig. 3, the n-Grid model in the Typhoon-HIL comprises a controller for an EV charger, a PV, and a fixed Battery storage with their common power electronic inverters. According to the schematics shown in Fig. 4 the distribution grid in the RTDS has an embedded n-Grid model which receives its operating signals from the Typhoon-HIL controller in real-time.

The connection between the two real-time simulators is shown in Fig. 5. The active and reactive powers consumption/generation of the n-Grid energy resources are sent to the GTNET communication link in RTDS via ETH blocks. Ethernet is used for connection based on the UDP communication protocol. The GTNET blocks receive the aforementioned signals from the Typhoon and transfer them to

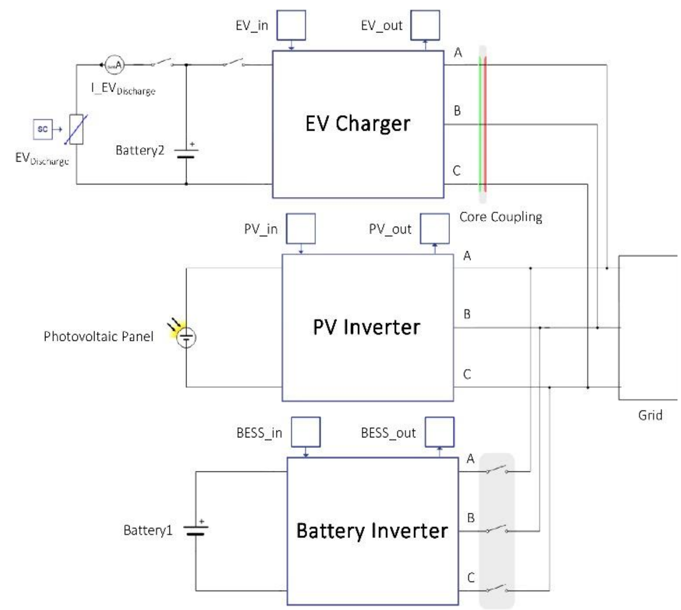


Fig. 3 The n-Grid controller in Typhoon-HIL.

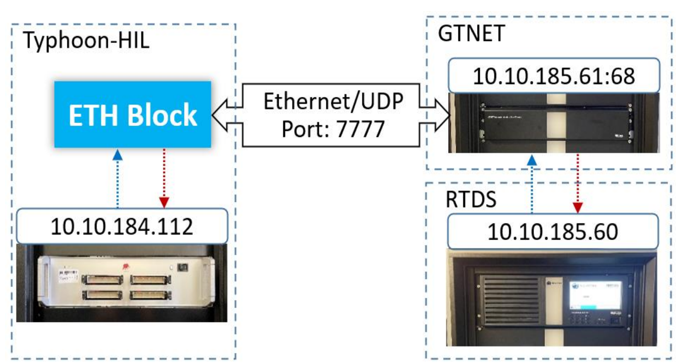


Fig. 5 Connection between the n-Grid controller in Typhoon-HIL and the distribution grid in RTDS.

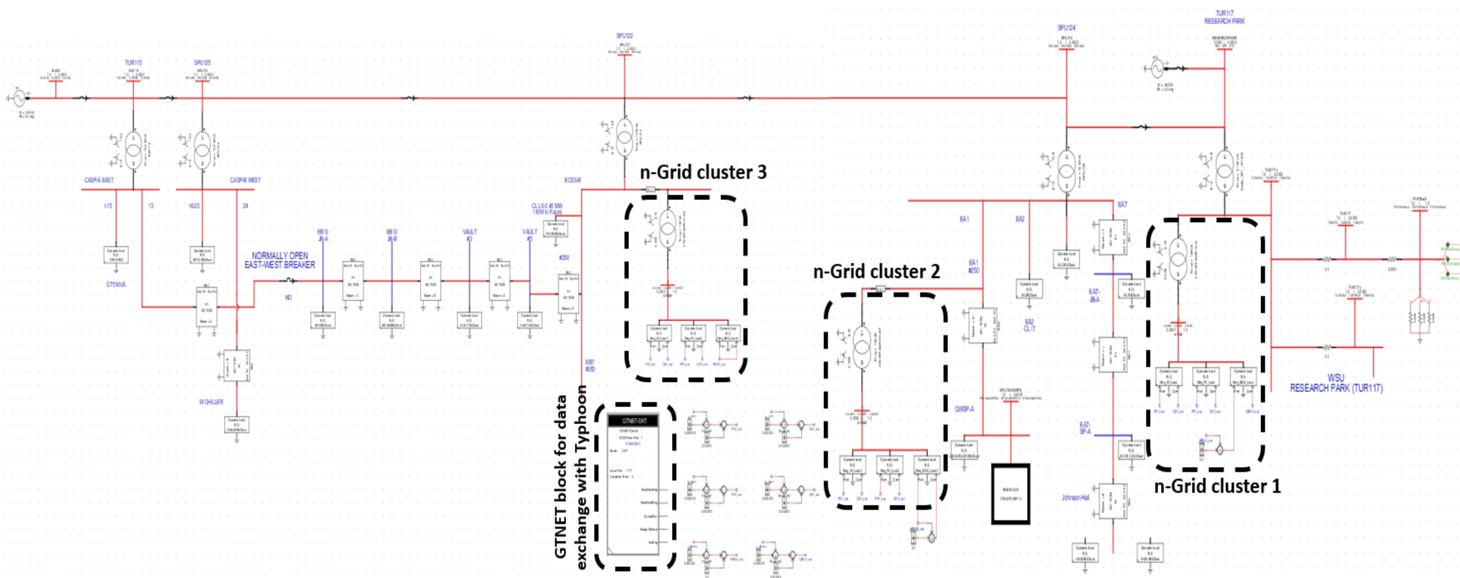


Fig. 4 The distribution grid and the n-Grid model in the RTDS.

the distribution grid model in the RTDS. The RTDS runs the power flow in time-domain based on the power signals received from Typhoon-HIL and updates the node voltages and line currents.

The model and specifications of the equipment used in the testbed are provided in Table I.

B. Testbed Use Cases

The aggregator and distribution utility can evaluate the impacts of ancillary service product delivery by n-Grids on the distribution grid by emulating the interactions using the testbed. They can also estimate the limits the distribution grid poses to such scenarios. The evaluation of the distribution grid constrains reflects on the type and amount of energy exchange services an n-Grid can offer. The testbed enables the financial evaluation of ASP procurement by the aggregation of n-Grids, and the expected profitability of aggregators and n-Grids owners from ASP delivery. This emulated connection can be helpful before actual field implementation since the financial/technical risks of such use cases can be evaluated.

This testbed can be enhanced to conduct hardware in the loop (HIL) test scenarios where actual inverters and associated equipment may be connected, which is beyond the scope of this paper. Such test use cases may assist the utility grid planners and n-Grid investors with evaluating the impacts of DERs on the power grid and offering solutions to mitigate such potential impacts in variety of use cases reflecting specific equipment.

TABLE I. TESTBED EQUIPMENT SPECIFICATIONS

Equipment	Model	Specifications
	Typhoon HIL 604	• Processor: Zynq-7 SoC • Power: 110 - 240 V 50/60 Hz • IO: 32 x Analog inputs 64 x Analog outputs 64 x Digital inputs 64 x Digital outputs
	RTDS NovaCor 1.0	• Processor: IBM® POWER8® RISC 10 cores @ 3.5 GHz • Power: 450 W, 100-240 V, 50/60 Hz • Scalability: 10 licensed cores per chassis 144 interconnected chassis
	RTDS GTNET Chassis	• Voltage: 100-240 V • Frequency: 50/60 Hz

C. Testbed Impacts

The impacts the use cases evaluated in our testbed may be grouped in several classes:

- Social Impact: The n-Grids are owned by electricity end-users and ensuring their profitability can make n-Grids more attractive leading to large-scale n-Grid deployment across the grid service territory.
- Regulatory Impact: The electricity consumers can have a key role in the support of the net-zero carbon grid implementation goals by owning n-Grids that can offer services towards that goal.
- Financial Impact: The n-Grid owners and aggregators can be reimbursed for offering its resources for energy trading and ASP procurement creating profits.
- Market Impacts: The ISO operators can assure improved reliability and flexibility enabled by n-Grid resource storage/generation capacities through offering ASPs.
- Utility Impacts: The n-Grids can also provide back-up services in case of the grid outages allowing utility companies to better manage outages.

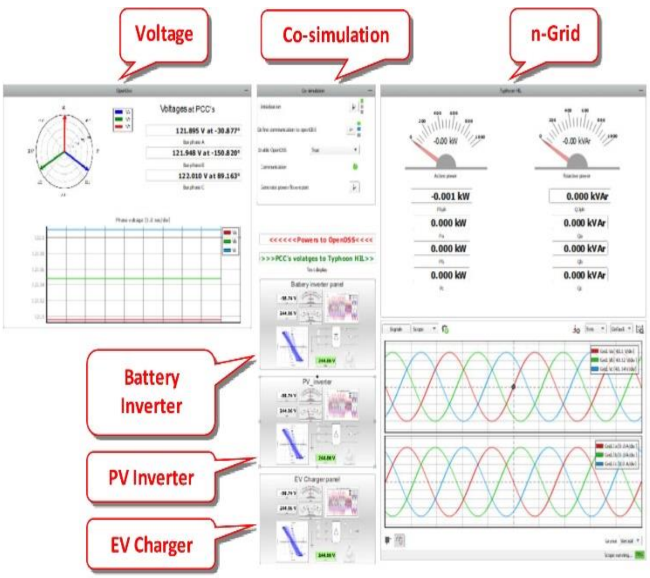


Fig. 6 N-Grid controller user-interface in the Typhoon-HIL SCADA.

IV. Case Study

A. Main Assumptions

In the distribution grid shown in Fig. 4, we consider 200 n-Grids connected to 3 feeders through a 208V/4.18kV transformer (40 n-Grids in feeder 1, 80 in feeders 2 & 3). Each n-Grid can deliver up to 5 kW of spinning reserve (SR) ASP (1 MW in aggregate). The n-Grid SR capability comes from its BESS and/or EV storage capacities. The SCADA system for the n-Grid controller in Typhoon-HIL is shown in Fig. 6. Assessing the SR delivery impacts on the node voltages and line currents is done by observing the impacts of delivering 1 MW of spinning reserve by the 200 n-Grids in two Use Cases (UCs) representing congested (UCI) and non-congested (UCII) distribution grid:

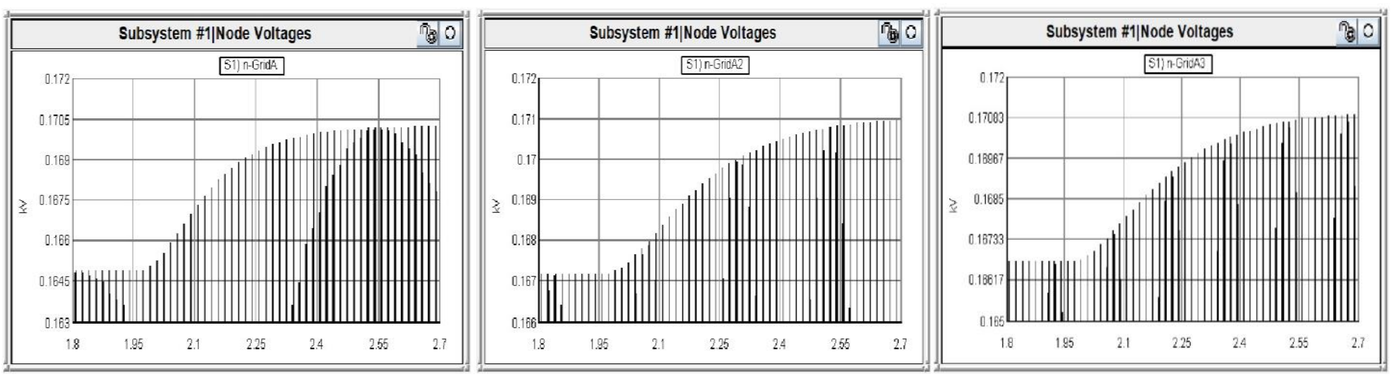
- UCI: Peak hours with total load of 11.90 MW.
- UCII: Off-peaks with total load of 5.95 MW.

B. Impact on Voltage Profiles

The impacts of delivering 1 MW of SR by the n-Grids on the voltage profile of their immediate distribution grid feeder in UCI and UCII are captured and depicted in Fig. 7 and Fig. 8, respectively. As it is observed, the n-Grid SR delivery improved the voltage profile in both use cases. The SR delivery is accomplished through extra power generation or load reduction, which in a grid with majorly passive loads leads to load reduction and voltage profile improvement. It also was observed that the voltage profile improvement in UCI is more significant than UCII. The initial voltage levels in UCI are lower, and reducing the line currents through SR delivery has more substantial effect on the grid voltages. For the 3 feeders with n-Grids in UCI, the lowest and highest voltage improvements were 2.6% in feeder 2, and 3.5% in feeder 1. For UCII, these numbers were 0.9% in feeder 1, and 1.2% in feeder 2.

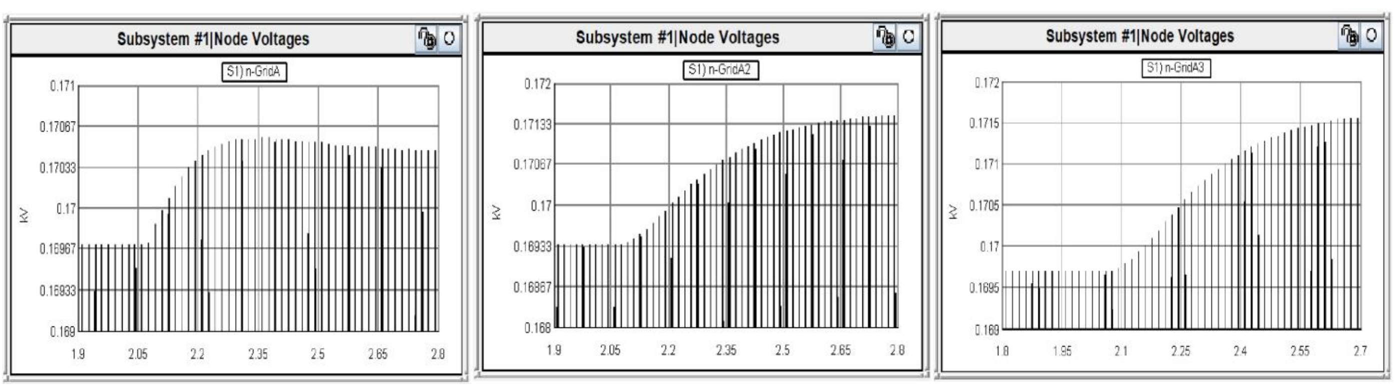
C. Impact on Line Currents

The impacts of delivering 1 MW of SR by the n-Grids on the main feeder current in UCI and UCII are depicted in Fig. 9. The main feeder is a 13.8 kV substation. The decrease in the current



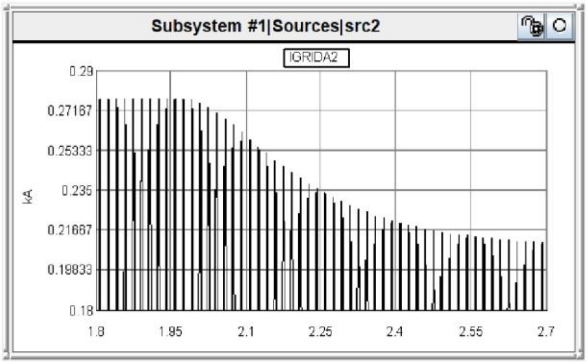
(a) (b) (c)

Fig. 7 Feeder voltage profiles as a result of SR delivery by n-Grids in UCI. (a) n-Grid cluster 1, (b) n-Grid cluster 2, and (c), n-Grid cluster 3.

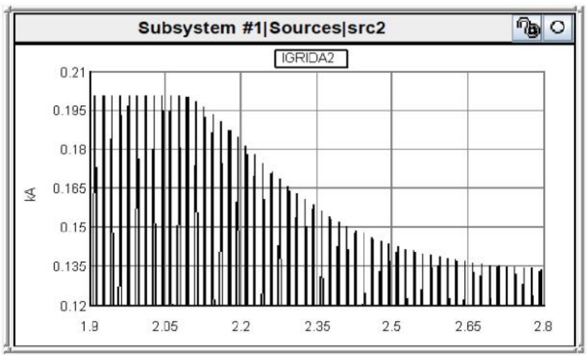


(a) (b) (c)

Fig. 8 Feeder voltage profiles as a result of SR delivery by n-Grids in UCII. (a) n-Grid cluster 1, (b) n-Grid cluster 2, and (c), n-Grid cluster 3.



(a)



(b)

Fig. 9 Current profiles in the main feeder as a result of SR delivery by n-Grids in: (a) UCI, (b) UCII.

in UCI and UCII were 66 A, and 63 A, respectively. The current drop in UCI is slightly higher than UCII, which stems from the higher line losses in higher current levels. The decrease in the main feeder current was 23.6% in UCI and 31.5% in UCII.

It approximately took 0.9 seconds for the voltage and current transient waves to die for the system to reach a new steady state.

V. Conclusions

The testbed allowed us to demonstrate that:

- Real-time simulators offer the flexibility needed to evaluate impacts of DERs on the electric grid when delivering ASPs.
- SR delivery by n-Grids improves the node voltage profiles and mitigates distribution line congestion in a grid with largely passive loads.
- The effects of n-Grid ASP delivery on the grid constraints are more significant in peak hours than off-peak hours.

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References

[1] M. Soleimani, M. Khoshjahan and M. Kezunovic, “Risk-based residential demand side response,” *CIRED Conference*, Geneva, Switzerland, September 2021.

[2] M. Soleimani, M. Khoshjahan and M. Kezunovic, “Reducing probability of transformer failure by managing EV charging in residential parking lots,” *IEEE PES General Meeting*, July 2021.

[3] M. Khoshjahan, M. Kezunovic, “Blockchain implementation for DER visibility and transaction verification in wholesale market,” *IEEE PES Transmission & Distribution (T&D) Conference & Exposition*, New Orleans, USA, April 2022.

[4] M. Kezunovic, M. Khoshjahan, M. Soleimani, “The future role of active distribution load in enhancing reliability, resilience and security of the electricity grids,” *CIGRE Symposium: Power System Transformation including Active Distribution*, Kyoto, Japan, April 2022.

[5] M. Kezunovic, M. Khoshjahan and M. Soleimani, “Harvesting the nano-Grid flexibility” *2021 CIGRE Grid of the Future Symposium*, Providence, Rhode Island, USA, October 2021.

[6] M. Khoshjahan, M. Soleimani and M. Kezunovic, “Tracing and securing DER transactions in the wholesale electricity market using blockchain,” *2021 IEEE PowerTech Conference*, Madrid, Spain, June 2021.

[7] M. Khoshjahan, R. Baembitov and M. Kezunovic, “Informed prosumer aggregator bidding strategy via incorporating distribution grid outage risk predictions,” *IEEE Access*, Vol. 11, pp. 28585-28595, March 2023.

[8] M. Khoshjahan, M. Soleimani and M. Kezunovic, "Optimal participation of PEV charging stations integrated with smart buildings in the wholesale energy and reserve markets," *IEEE PES Conference on Innovative Smart Grid Technologies North America*, Washington, D.C., Feb. 2020.

[9] M. Khoshjahan, R. Baembitov and M. Kezunovic, "Impacts of weather-related outages on DER participation in the wholesale market energy and ancillary services," *2021 CIGRE Grid of the Future Symposium*, Providence, RI, October 2021.

[10] M. Kezunovic, R. Baembitov and M. Khoshjahan, “Data-driven state of risk prediction and mitigation in support of the net-zero carbon electric grid,” *IREP Bulk Power System Dynamics and Control Symposium*, Banff, Canada, July 2022.

[11] M. Khoshjahan, and M. Kezunovic, “Cybersecurity analysis of prosumer/aggregator communications via software defined networking emulators,” *CIRED Workshop on E-mobility and power distribution systems*, Porto, Portugal, June 2022.

[12] M. Khoshjahan, M. Fotuhi-Firuzabad, M. Moeini-Aghtaie and P. Dehghanian, “Enhancing electricity market flexibility by deploying ancillary services for flexible ramping product procurement,” *Electric Power Systems Research*, Vol. 191, pp. 106878, 2021.

[13] M. Khoshjahan, P. Dehghanian, M. Moeini-Aghtaie and M. Fotuhi-Firuzabad, “Harnessing ramp capability of spinning reserve services for enhanced power grid flexibility,” *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 7103-7112, Nov.-Dec. 2019.

[14] M. Khoshjahan and M. Kezunovic, “Robust bidding strategy for aggregation of distributed prosumers in flexiramp market,” *Electric Power Systems Research*, Vol. 209, 107994, August 2022.

[15] MD Omar Faruque *et al.* “Real-time simulation technologies for power systems design, testing, and analysis,” *IEEE Power and Energy Technology Systems Journal*,vol. 2, no. 2 pp. 63-73, 2015.

[16] R. Gagnon, et al., “Large-scale real-time simulation of wind power plants into Hydro-Québec power system,” *9th International Workshop on Large-Scale Integration of Wind Power into Power Systems*, 2010.

[17] G. Sybille and P. Giroux, “Simulation of FACTS controllers using the MATLAB power system blockset and Hypersim real-time simulator,” *IEEE Power Engineering Society Winter Meeting*, vol. 1, pp. 488-491, New York, NY, USA, 2002.

[18] H. Li, M. Steurer, K. L. Shi, S. Woodruff and D. Zhang, “Development of a unified design, test, and research platform for wind energy systems based on hardware-in-the-loop real-time simulation,” *IEEE Transactions on Industrial Electronics*, vol. 53, no. 4, pp. 1144-1151, June 2006.

[19] X. Guillaud et al., “Applications of real-time simulation technologies in power and energy systems,” *IEEE Power and Energy Technology Systems Journal*, vol. 2, no. 3, pp. 103-115, Sept. 2015.

[20] A. R. Al-Ali, R. Gupta, and A. Al Nabulsi, “Cyber physical systems role in manufacturing technologies,” *AIP Conference Proceedings AIP Publishing LLC*, vol. 1957, no. 1, 2018.

[21] https://www.typhoon-hil.com

[22] https://www.rtds.com