Impact of Unbalanced Partial Tripping of Large Electronic Loads on Local Power Quality

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***Abstract*— The rapid growth of Large Electronic Loads (LELs) is reshaping the bulk power system. Unlike conventional industrial loads, LELs rely heavily on power electronics, making them highly sensitive to voltage disturbances. Field observations show that single-phase voltage sags occurring far from the LEL's point of interconnection (POI) can trigger unbalanced partial tripping, causing large negative- and zero-sequence currents that flow through nearby transformers and equipment. These circulating currents can cause magnetic core saturation, equipment overheating, harmonic distortion, protection malfunctions, and even ferroresonance. This paper emulates the behavior of a real-world partial-tripping event in Far West Texas region of ERCOT using electromagnetic transient (EMT) simulations and evaluates how unbalanced tripping can generate negative- and zero-sequence currents at the POI. The effect of different transformer windings is considered.**

Index Terms—Large Electronic Load (LEL), Cryptocurrency mining, Partial Tripping, Transformer Saturation.

I. INTRODUCTION

Large Electronic Loads (LELs), including data centers and cryptocurrency (crypto) mining facilities, are no longer niche components of the grid; they are becoming impactful and transformative forces shaping both operational and planning horizons [1]. In the United States, data centers already represent a major and growing share of electricity demand, accounting for about 4% of total load in 2023 and potentially reaching up to 9% by 2030 [2]. This unprecedented expansion underscores their increasing influence on bulk power system planning and reliability considerations [2], [3].

Within the Electric Reliability Council of Texas (ERCOT) system, the rapid integration of LELs, particularly data centers and cryptocurrency mining operations, has become a focal point. As of early 2025, ERCOT had approved over 6,300 MW of large-load interconnections, with peak simultaneous consumption reaching approximately 3,100 MW [4], [5]. Most of these loads are mainly power-electronic in nature and, therefore, sensitive to voltage disturbances and they are mostly concentrated in regions such as West Texas [6].

ERCOT operations have documented numerous cases of LELs exhibiting significant partial power tripping following single-line-to-ground (SLG) faults. From January 2023 to August 2025, 26 events occurred in which at least 100 MW of LELs were lost, with power reductions ranging from 20% to 100% of pre-disturbance consumption [4], [5].

These events consistently demonstrate that the faulted phase experiences the most severe loss, while other phases draw unbalanced power [5]. In some cases, the unbalanced condition can persist long after fault clearing [5]. Such persistent imbalance indicates that post-disturbance recovery does not occur uniformly across all phases, leading to unequal voltages and currents that extend beyond the transient phase. More critically, these conditions can produce sustained zero- and negative-sequence components, which can propagate through the LEL collector system and drive nearby transformers into magnetic saturation. This leads to increased harmonic distortion at the POI, excessive heating, protection malfunctions, and oscillatory behavior.

In this paper, we emulate a real-world LEL partial tripping event within the ERCOT system using EMT simulations based on Digital Fault Recorder (DFR) data [5]. First, the partial tripping behavior is validated against field measurements. Next, we analyze the sequence components and harmonics of voltage and current at the LEL's POI, generated by unbalanced conditions following partial tripping. To evaluate the impact of winding configuration on both voltage and current unbalanced factors (UFs), we perform simulations using different winding arrangements for both main power transformer (MPT) and the facility internal transformer (FIT). The results show that using a Yg–Δ configuration for MPT and a Δ–Yg for FIT effectively suppresses zero-sequence propagation, while negative sequence remains unchanged.

This paper is organized as follows. Section II provides further discussion on partial tripping of LELs in ERCOT. Section III describes EMT case study setup and simulations, emulating a partial tripping event. Section IV presents EMT simulation results, and finally, Section V concludes the paper.

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II. Partial Tripping of LELs in ERCOT

One of the most illustrative examples of partial tripping in Far West Texas occurred on November 18, 2024, during a 345 kV SLG fault that was cleared within four cycles [5]. At the time of the event, the aggregate pre-disturbance demand across several crypto facilities was approximately 625 MW. The disturbance caused a total 197 MW (31%) power reduction among affected crypto facilities [5]. Among the affected facilities, one in particular, Facility L, was interconnected at 138 kV level, experienced an 18% (23 MW) power reduction following the SLG fault on phase B, as shown in Fig. 1. DFR data indicate that Facility L operated in a balanced condition before the fault. After fault clearance, the facility operated unbalanced for some time, with the faulted phase power sustaining most of the reduction, as shown in Fig. 1. Unlike typical loads, which return to normal balanced operation after a fault is cleared, Facility L continued operating in a partially tripped condition, drawing unbalanced power from the grid. This unbalanced condition generated large negative- and zero-sequence current components. These currents introduced harmonics and drove transformers toward magnetic saturation, leading to equipment overheating, poor power quality, protection misoperation, and interfering with operational control.

III. EMT Case Study Setup and Simulations

This section describes the EMT simulation setup developed for Facility L to emulate the unbalanced partial tripping event shown in Fig. 1. The simulation focuses on capturing three key features observed during the actual event:

- Voltage sag on the faulted phase to nearly 0.6 pu.
- Unbalanced partial load reduction to about 15–20% of pre-disturbance power.
- Persistent unbalanced power consumption after the fault clearance.

The EMT model of Facility L and the associated transmission system, shown in Fig. 2, includes the collector system, main power transformer, transmission line, and equivalent voltage source showing the upstream network. The parameters of the transmission line and the voltage source are listed in TABLE I, with impedances per-unitized based on 100 MVA and 138 kV base.

Since detailed information on the collector system was not available [8], it was modeled using generic parameters commonly used. TABLE II summarizes the data used for modeling the main transformer, including its saturation characteristics, as well as the facility internal transformer (low- to medium-voltage) and cable system [9], [10].

As noted earlier, due to the absence of a detailed EMT model of Facility L [8], the facility load was represented using single-phase constant-power elements, with approximately 40 MW per phase, totaling about 130 MW under normal operating conditions. A simplified voltage-threshold–based ride-through logic was implemented to trip approximately 20% of the total load, thereby emulating the post-fault unbalanced partial tripping behavior consistent with the real event shown in Fig. 1.

IV. EMT Simulation Results

In this section, the EMT simulation results obtained from the Facility L model are presented. As shown in Fig. 3, a SLG fault was applied on phase B at t = 2 s and cleared after four cycles. The fault was placed at the Thevenin equivalent bus with a 1.2 Ω impedance, producing a voltage sag of approximately 0.6 pu on the faulted phase at the POI, consistent with the real event shown in Fig. 1. Following fault clearance, the power on phase B decreased sharply, resulting in an overall three-phase power reduction of about 20%, closely matching field observations. The agreement between the simulation results and the DFR measurements suggests that the Facility L is utilizing a Yg–Yg winding configuration for both the MPT and FIT transformers, a behavior that cannot be replicated using the Yg–Δ configuration. The model successfully reproduces the unbalanced partial tripping behavior observed during the actual event and can therefore, serve as a foundation for examining transformer saturation, zero-sequence current behavior, and harmonic distortion.

Fig. 1. Voltage and per-phase/total active power of three phases of Facility L at the event of Nov. 18, 2024 [5].

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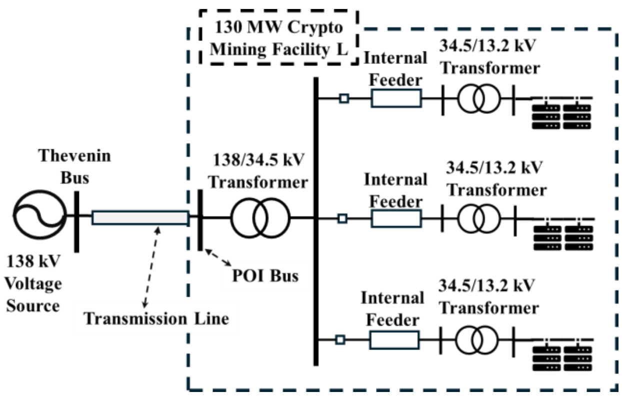

Fig. 2. Schematic of Facility L connecting to the equivalent source.

TABLE I. Parameters of Equivalent Transmission System

Parameters	Values
Voltage Source	
Base Voltage	138 kV
Base Frequency	60 Hz
Total MVA Rating	100 MVA
Impedance: Magnitude and Angle	1.07ohm, 22 degrees
Transmission Line	
Model type	PSCAD Bergeron model
Positive Sequence Resistance	0.002 pu
Positive Sequence Inductive Reactance	0.050 pu
Positive Sequence Capacitive Susceptance	0.225 pu

TABLE II. Parameters of Collector System and Main Transformer

Parameters	Values
Main power transformer (MPT)	
Winding Ratio	138/34.5 kV (Y-Y)
Rated Power	100 MW
Positive Sequence Leakage Reactance	0.1 pu
Magnetization Model	Jiles-Atherton Hysteresis
Nominal Magnetizing Flux Density	1.667 [T]
Air-Core Reactance	0.2 pu
Collector System	
Facility's Internal Transformer (FIT)	
Winding Ratio	34.5/13.8 kV (Y-Y)
Rated Power	100 MW
Positive Sequence Leakage Reactance	0.1 pu
Magnetization Model	Jiles-Atherton Hysteresis
Nominal Magnetizing Flux Density	1.667 [T]
Air-Core Reactance	0.2 pu
Cables Modeled by PI Section	
Positive Sequence Resistance	0.01781 Ω
Positive Sequence Inductive Reactance	0.3138 Ω
Positive Sequence Capacitive Reactance	273.54 10^2 Ω
Zero Sequence Resistance	0.2952 Ω
Zero Sequence Inductive Reactance	1.0398 Ω
Zero Sequence Capacitive Reactance	414.16 10^2 Ω

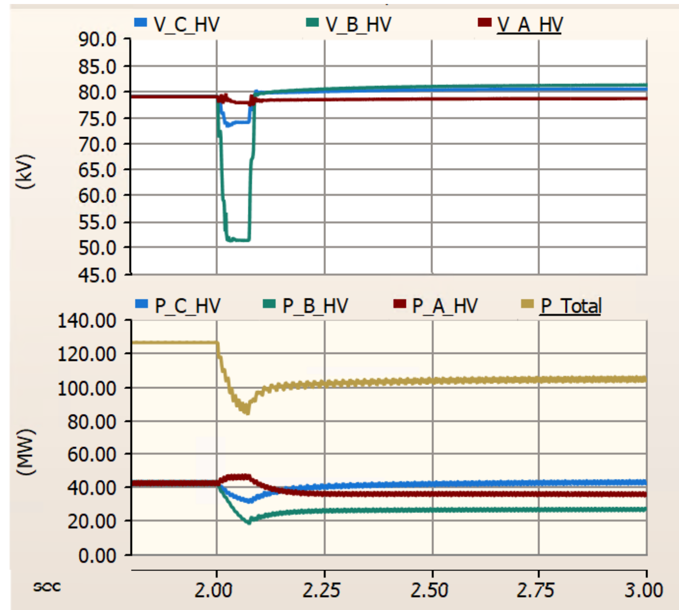

Fig. 3. Emulation of the real-world event: Phase voltages and per-phase/total active powers.

Fig. 4 shows ground current (I_g_HV), magnetizing currents, and flux linkages of the MPT supplying Facility L. Following the fault clearance, the unbalanced load power caused a substantial increase in ground current, producing a sustained zero-sequence current through the transformer neutral. The continuous flow of ground current induces a gradual flux offset within the core [10], resulting in an unbalanced excitation. The magnetizing currents in Fig. 4 show that the transformer excitation current becomes highly unbalanced, with Phase B reaching more than 40 % of the rated current. The corresponding flux linkages in Fig. 4, expressed in per-unit, reach almost 2.0 p.u., indicating that the core entered magnetic saturation under unbalanced phase currents.

Fig. 5 shows the sequence components on the high-voltage side (138 kV) of the MPT. The results show that the negative-sequence current remained above 0.2 pu for an extended duration and the zero-sequence current exceeded 0.4 pu, indicating a risk of transformer saturation and potential ferroresonance with other capacitive system components [11], [12].

According to IEEE Std 519-2022, the primary reference for harmonic limits [13], for systems rated between 69 kV and 161 kV with $I_{SCR}/I_L < 20$, the recommended maximum current total demand distortion (TDD) at the POI is 5%, and the corresponding voltage total harmonic distortion (THD) limit is 1.5% [13]. Fig. 6 shows the TDD of phase currents and THD of phase voltages on the 138 kV side of the MPT. Under unbalanced operating conditions, both TDD and THD rise sharply during transients and gradually decline after fault clearance. Phase B current TDD exceeds 30% and remains above 5% for about one second, while phase B voltage THD peaks at

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10% immediately after fault clearance and stays above 1.5% for roughly two seconds.

To evaluate the impact of transformer winding configuration on voltage and current unbalance factors (UFs) at the MPT high voltage side, additional simulations were performed with different winding arrangements for both MPT and FIT. Specifically, the MPT configuration was changed from Yg-Yg to Yg–Δ, and FIT from Yg-Yg to Δ–Yg.

TABLE III summarizes how these winding configurations impact the UFs of voltage and current. The first column defines the UFs for negative- and zero-sequence components at the LEL's POI. When both transformers are configured as Yg-Yg, the negative-and zero-sequence currents propagate through the transformers, resulting in UF values within the problematic range reported in [13].

For example, the UFs of ~23% negative-sequence current and 3.22% zero-sequence current exceed the problematic range reported in [14]. However, using Yg–Δ for the MPT and Δ–Yg for the FIT effectively suppressed the zero-sequence current UF, reducing the values to within the normal range.

This improvement occurs because the delta winding provides a circulating path that traps zero-sequence currents internally and prevents their propagation into the high-voltage network.

The UFs for negative-sequence voltage and current, however, remain largely unaffected, indicating that patrial tripping continues to induce negative-sequence unbalance on the transmission side, even with the delta configuration.

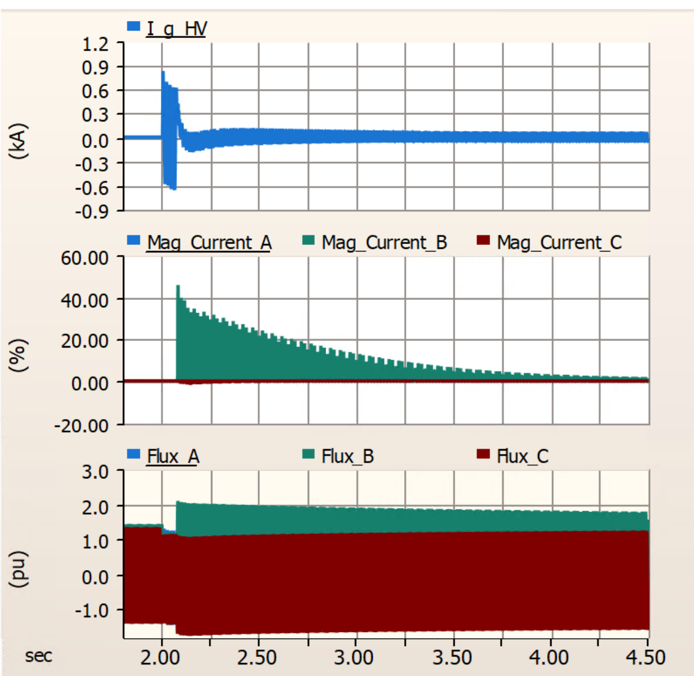

Fig. 4. Ground current, per-phase magnetizing currents and flux linkages of the MPT.

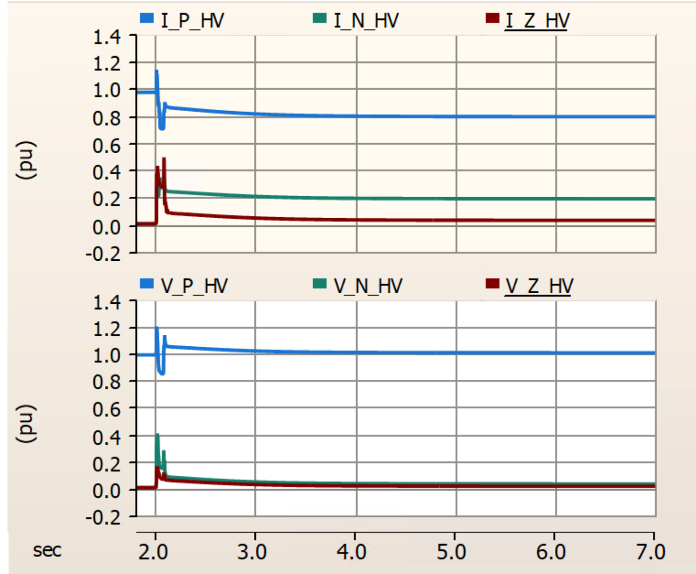

Fig. 5. Sequence quantities for phase voltages and currents on the 138 kV side of the MPT.

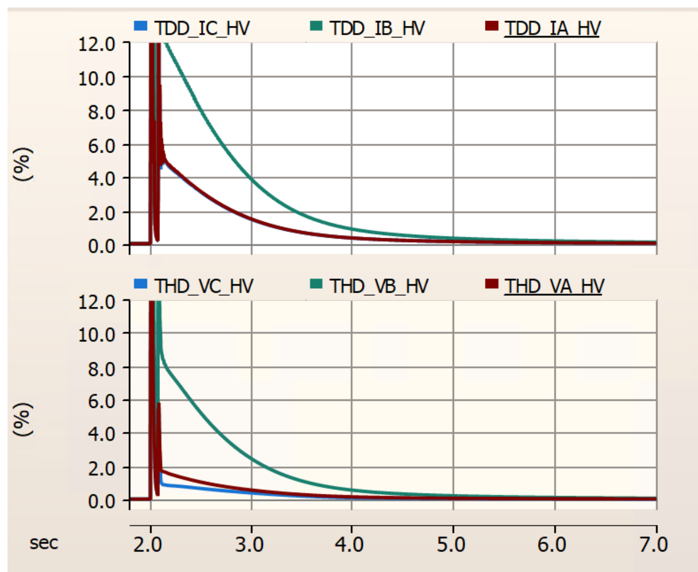

Fig. 6. Total harmonic distortion of the phase currents and voltages on the 138 kV side of the main transformer (Y–Y connection).

A final note: Δ–Yg transformers can potentially improve ride-through performance for cypto mining facilities that use single-phase equipment. This is because the Δ–Yg winding configuration will convert a single-phase transmission voltage sag to a significantly lessened voltage sag on two of the load phases.

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TABLE III. Winding Configuration Impact on Voltage and Current Unbalance Factor

Unbalance Factor (UF) for Voltage and Current	MPT and IFT Winding Configurations	
	Yg-Yg, Yg-Yg	Yg-Δ, Δ-Yg
$V_{N,HV}/V_{P,HV}$	2.80%	2.77%
$V_{Z,HV}/V_{P,HV}$	1.06%	0.02%
$I_{N,HV}/I_{P,HV}$	23.36%	23.18%
$I_{Z,HV}/I_{P,HV}$	3.22%	0.02%

V. CONCLUSIONS

This paper demonstrates that partial tripping of LELs creates unbalanced operating conditions that materially impact local power quality. EMT simulation results show that unbalanced post-fault recovery generates zero- and negative-sequence currents, exceeding 0.4 pu and persisting above 0.1 pu for several cycles, well beyond the fault-clearing period. These sequence components excite the transformer core asymmetrically, leading to magnetic saturation, elevated core losses, and increased thermal stress.

Additionally, the unbalanced operating conditions amplifies harmonic distortion. The total demand distortion (TDD) of phase currents and total harmonic distortion (THD) of voltages on the high-voltage side of the main power transformer (MPT) increase sharply during transients. TDD exceeds 30% and remains above 5% for about 60 cycles, while voltage THD peaks 10% and stays above 1.5% for roughly 120 cycles after fault clearance.

The analysis also highlights the critical role of transformer winding configuration. When both the MPT and Facility Internal Transformer (FIT) are configured as Yg–Yg, negative- and zero-sequence currents propagate through the transformers, resulting in unbalance factors (UFs) exceeding acceptable limits. However, using Yg–Δ for the MPT and Δ–Yg for the FIT effectively suppresses zero-sequence propagation white negative sequence remains unchanged. In addition, Δ–Yg transformers also have the potential to improve ride-through for SLG transmission faults.

These findings emphasize that partial tripping of LELs can lead to persistent unbalance conditions and harmonic distortion, and that proper transformer winding configuration plays a key role in mitigating zero-sequence effects and preserving overall system power quality.

Although this study focuses on a single cryptocurrency mining LEL facility, field data indicate that similar partial tripping can occur simultaneously across multiple LEL sites. Such concurrent partial tripping due to a single system disturbance poses broader power quality concerns.

REFERENCES

[1] Electric Power Research Institute (EPRI), *Powering Intelligence: Analyzing Artificial Intelligence and Data Center Energy Consumption*, White Paper, Palo Alto, CA, USA, May 2024.

[2] Elevate Energy Consulting, *Practical Guidance and Considerations for Large Load Interconnections*, GridLab-Supported Report, May 2025.

[3] A. J. G. de Vries, "Bitcoin's growing energy problem," Joule, vol. 2, no. 5, pp. 801–805, May 2018.

[4] P. Gravois, "ERCOT Large Load Loss/Reduction Events 2020–2024," presented at the ERCOT Operation Working Group (OWG) Meeting, Nov. 21, 2024. [Online]. Available: *https://www.ercot.com/files/docs/2024/11/19/ERCOT%20Large%20Load%20Events_OWG_21Nov2024.pdf*

[5] P. Gravois, "ERCOT Large Load Loss/Reduction Events 2020–2024," presented at the ERCOT Large Flexible Load Task Force (LFLTF) Meeting, Mar. 4, 2025. [Online]. Available: *https://www.ercot.com/files/docs/2025/02/28/ERCOT-Large-Load-Events_LFLTF_March2025.pptx*

[6] Y. Cheng, "Preliminary Load Loss Assessment of Operational Large Loads in ERCOT," presented at the ERCOT Large Load Working Group (LLWG) Meeting, May 16, 2025. [Online]. Available: *https://www.ercot.com/files/docs/2025/05/16/LoadLossPreliminaryAssessment_LLWG-05162025-.pptx*

[7] P. Gravois, "ERCOT Large Electronic Load Voltage Ride-Through Performance Requirements (Proposal)," presented at the ERCOT Large Load Working Group (LLWG) Meeting, Jul. 11, 2025. [Online]. Available: *https://www.ercot.com/files/docs/2025/07/11/ERCOT-LEL-Ride-Through-Criteria_LLWG-final.pptx*

[8] J. Billo, "Large Load Voltage Ride-Through Requirements," presented at the ERCOT Large Flexible Load Task Force (LFLTF) Meeting, Sep. 25, 2023. [Online]. Available: *https://www.ercot.com/files/docs/2023/09/22/LFLTF_Large%20Load%20VRT_09252023.pptx*

[9] M. Dolinar, D. Dolinar, G. Stumberger, B. Polajzer and J. Ritonja, "A three phase core-type transformer iron core model with included magnetic cross saturation," *Proc. 2006 IEEE International Magnetics Conference (INTERMAG)*, San Diego, CA, USA, 2006, pp. 356-356.

[10] G. A. D. Dias and A. Tamagna, "A case study of transformer saturation in distribution systems," *Proc. 9th Int. Conf. Harmonics and Quality of Power (ICHPQ)*, Orlando, FL, USA, 2000, pp. 864-867 vol.3.

[11] J. Pedra, L. Sainz, R. Lopez and S. Bogarra, "Transformer saturation model for the harmonic analysis on power systems," *Proc. 8th Int. Conf. on Harmonics and Quality of Power (ICHPQ)*, Athens, Greece, 1998, pp. 1053-1058 vol.2.

[12] G. Eduful, Y. Fan and A. Abu-Siada, "Simulation-Based Investigation of Ferroresonance in Different Transformer Configurations," *Proc. 2024 IEEE 9th Int. Conf. Adaptive Science and Technology (ICAST)*, Accra, Ghana, 2024, pp. 1-11.

[13] "IEEE Standard for Harmonic Control in Electric Power Systems," in *IEEE Std 519-2022 (Revision of IEEE Std 519-2014)*, pp.1-31, 5 Aug. 2022.

[14] *Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods*, IEC 61000-4-30, Ed. 3.2, International Electrotechnical Commission, Geneva, Switzerland, 2021.

979-8-3315-8138-1