Real Time Implementation of Microgrid Blackstart Using MATLAB-RSCAD Co-simulation

Mir Jubaier Hassan
Dept. of Electrical & Comp. Eng.
University of North Carolina at Charlotte
Charlotte, USA
mhassa14@charlotte.edu

Nahom Teklemariam
Dept. of Electrical & Comp. Eng.
University of North Carolina at Charlotte
Charlotte, USA
nteklema@charlotte.edu

Badrul Chowdhury
Life Senior Member, IEEE
Energy Production & Infastructure Center
University of North Carolina at Charlotte
Charlotte, USA
b.chowdhury@charlotte.edu

Robert Cox
Energy Production & Infastructure Center
University of North Carolina at Charlotte
Charlotte, USA
robert.cox@charlotte.edu

***Abstract*—After extreme weather events, service restoration of a microgrid is crucial for improving system resiliency. However, the dynamic behavior of loads, particularly during cold load pickup (CLPU), makes re-energization challenging and can introduce severe inrush conditions that stress the feeder and may lead to unnecessary protection operations or secondary outages. Most existing restoration strategies in the literature rely on steady-state optimization and do not capture these transient effects. To address this gap, this paper proposes a co-simulation-based restoration framework that combines an optimization-derived switching sequence in MATLAB with real-time electromagnetic transient simulation in RSCAD. The framework is applied to the IEEE 123-bus system, where loads are restored in multiple horizons, and the feeder-end response is monitored.**

***Index Terms*—Microgrid, Load Restoration, Co-simulation, RSCAD, Real-Time Simulation, Cold Load Pickup**

I. Introduction

In recent years, the concept of microgrids has emerged as a transformative approach to improve power system resilience, especially under extreme conditions such as extreme weather events, cyberattacks, or large-scale system faults. In such contexts, rapid and efficient restoration of critical loads is essential to support essential services and reduce socioeconomic impact, where microgrids, with their capability to operate independently from the main grid, play a pivotal role in service restoration. The restoration process must account for system dynamics, prioritization of critical infrastructure, and operational constraints, making it a highly complex decision-making problem [1], [2].

A key part of this challenge is developing optimized restoration sequences that determine the order and timing for closing switches and restoring loads. Optimization methods such as mixed-integer linear programming (MILP) [3], [4] and second-order cone programming (SOCP) [5], robust or stochastic methods [6], [7] etc., have been successfully used to formulate restoration as a constrained decision problem. These formulations aim to maximize load restoration or minimize restoration time while ensuring radial topology, voltage and frequency constraints, and prioritization of critical loads. However, while these approaches provide a theoretically optimal switching sequence, they are typically implemented in offline environments and do not consider real-time factors such as cold load pickup (CLPU) or transient system behaviors. In recent works, CLPU phenomenon was also introduced in these restoration approaches because of its significant impacts in the restoration sequence [8].

CLPU is a well-known phenomenon in restoration planning, where thermostatically controlled loads (TCLs) like air conditioners or water heaters lose their operating diversity after an outage and tend to switch on simultaneously upon re-energization, resulting in a surge that can be 2–5 times the steady-state demand [9], [10]. To model the CLPU different load models have been used in literature among which the most practical model is the delayed exponential model (DEM) which was validated by different methods [10], [11]. CLPU can cause significant voltage drops and frequency deviations that may trigger protection schemes, delay restoration, or even cause partial system collapse. So, validating the restoration sequence derived from the algorithm becomes essential considering the real world circumstances.

To bridge this gap, real-time digital simulation platforms, such as RSCAD running on RTDS, offer a high-fidelity environment for testing and validating restoration strategies. These platforms allow for detailed modeling of the dynamics of the system, including load transients, control delays, and network reconfiguration [12]. However, integrating optimized restoration outputs into such platforms in real-time—especially while accounting for CLPU and complex switching logic—remains an underexplored domain then in the literature.

This paper presents a co-simulation framework that connects MATLAB (for optimization and control) with RSCAD (for

979-8-3315-8138-1

real-time electromagnetic transient simulation) to implement and validate black-start restoration strategies in a microgrid setting. A TCP socket interface enables real-time communication between MATLAB and RSCAD, allowing the transfer of optimized switching sequences. The methodology is validated in the IEEE 123-bus test feeder. The findings of the paper can reduce the gaps between the theoretical and practical approaches of service restoration of microgrids.

II. Methodology

A. Restoration Framework

The optimization algorithm is formulated using a MILP model in MATLAB. A 2 MW battery is used as the black start unit, with a maximum load step of 250 kW. At the start of the simulation, the black start unit is activated without delay. All lines are treated as non-switchable, while all loads are considered switchable with equal criticality. Additionally, the voltage at bus 1, where the battery is connected, is maintained at 1 p.u. throughout the simulation. The complete formulation of the optimization model and its implementation process are detailed in the authors' previous work [13], and only a brief overview is provided here for completeness.

The optimization algorithm includes several constraints, such as load flow constraints, maximum load step constraints, voltage limit constraints, and CLPU constraints. The objective is to maximize the total base load restored in each horizon as given by equation (1).

$$\max \sum_{l \in L} \sum_{t \in T} w_l \cdot \left(\sum_{\phi \in \{a,b,c\}} P_{l,t}^{\phi} \right) \tag{1}$$

where w_l is the criticality weight assigned to load l, $P_{l,t}^{\phi}$ is the active power consumed by a load l per phase $\phi \in \{a, b, c\}$ at time horizon t, L is the set of all loads, and T is the set of all time horizons.

All loads are modeled using CLPU characteristics based on the DEM. The decay rate is chosen so that the undiversified load decays within 4 horizon. Each time horizon in the simulation is 240 seconds long, and the simulation spans 10 time horizons. Additionally, the undiversified load is set to 2.5 times the diversified load. After executing the optimization algorithm, optimal load restoration sequences that satisfy all MILP model constraints are obtained.

B. Co-simulation Framework

The implementation of the optimized load restoration strategy under real-time operating conditions can be achieved using a co-simulation framework of MATLAB and RSCAD through a TCP/IP socket-based communication protocol. In this setup, MATLAB works as the supervisory controller, which computes the optimized switching sequence, and RSCAD, operating on the RTDS platform, executes the switching signals received via socket communication and simulates system-wide electromagnetic transients during the restoration process.

The co-simulation operates over multiple discrete restoration horizons, with each horizon corresponding to a time interval during which a subset of loads is restored. For every horizon, MATLAB identifies the switches to be closed based on the optimal derived sequence. MATLAB formats this information into a structured data packet and transmits it to RSCAD using a TCP socket interface. Upon receiving the data, RSCAD parses the message and applies the control signals accordingly. It triggers the closure of the specified switches, ensuring current flow to the loads.

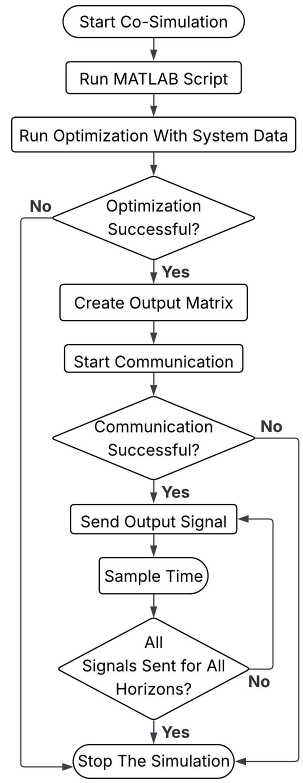


Fig. 1: Flowchart of the implemented co-simulation of MATLAB and RSCAD

The simulation proceeds in a synchronized manner using a fixed delay between two consecutive transmitted data packets. This maintains the constant time gap between two consecutive horizons and ensures accuracy during restoration. The complete workflow of this co-simulation process is illustrated in Fig.1, which outlines the step-by-step interaction between MATLAB and RSCAD. This real-time co-simulation framework ensures that the optimized restoration strategy is not only theoretically sound but also practically viable under dynamic system conditions, including CLPU effects.

C. Modeling

This study uses the IEEE 123-bus test feeder to evaluate the performance of the real-time co-simulation framework. The IEEE 123-bus system is a large-scale, unbalanced, three-phase distribution network widely used as a benchmark for restoration and reliability studies. The system is initially de-energized, and a predefined set of switches is opened for

979-8-3315-8138-1

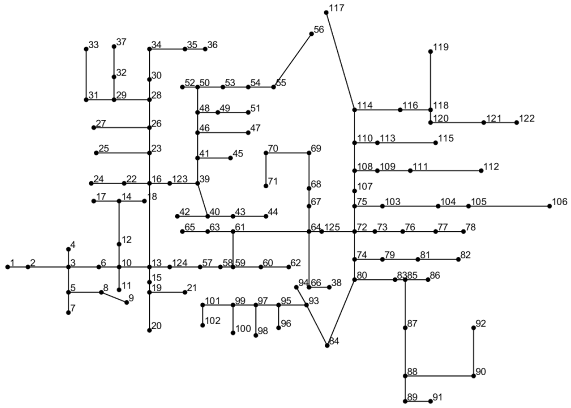


Fig. 2: Unenergized IEEE-123 bus microgrid

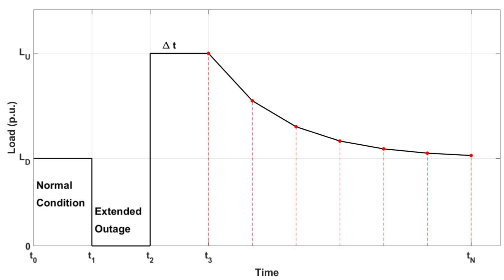


Fig. 3: CLPU characteristic curve

stepwise restoration. Loads are placed at multiple locations and restored through coordinated switch closing. A simplified layout of the system in its unenergized state is illustrated in Fig.2.

To model the cold load pickup behavior, the DEM model was used because of its ability to capture the inrush effect commonly observed during post-outage load restoration, which is depicted in Fig. 3. For load modeling in RSCAD, dynamic load models and scheduler control were used simultaneously. Typically, a scheduler is employed to model time-series loads, where it takes inputs from a file which contains the time and load values. In this case, the file contains the load behavior of a standard 1 MW load under CLPU conditions. This profile is then multiplied by the base power of the actual loads, and the result becomes the P and Q setpoints of the dynamic loads. To ensure synchronism between the switch trigger and load calculation, an enable switch was incorporated into the scheduler. The scheduler starts when this enable switch is activated, and the switching signal of the load serves as the input to this enable switch. This combined load modeling approach can replicate the DEM behavior, which cannot be modeled in RSCAD using other existing load models such as ZIP, constant PQ, polynomial, or exponential.

Other components of the system are also modelled in RSCAD to ensure realistic simulation. The distribution lines are represented using constant parameter line models with phase-specific impedance. Switches are implemented as ideal breakers controlled by external signals received from MATLAB. The substation is modelled as an ideal balanced three-phase voltage source, and no distributed generation, protection relays, or fault conditions are considered in this study. All components are simulated with a fixed EMT time step to ensure numerical stability.

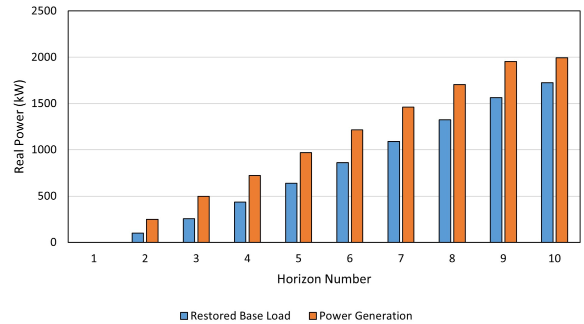


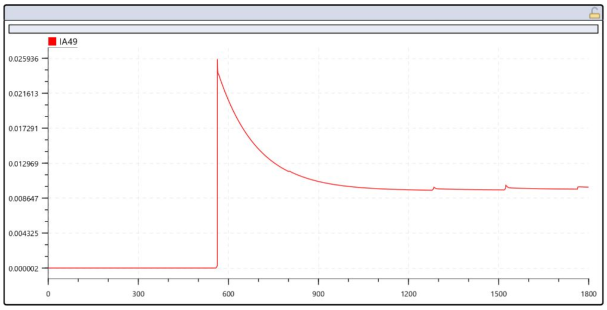
Fig. 4: Cumulative active power generation vs base load restored for each horizon

III. Results and Discussion

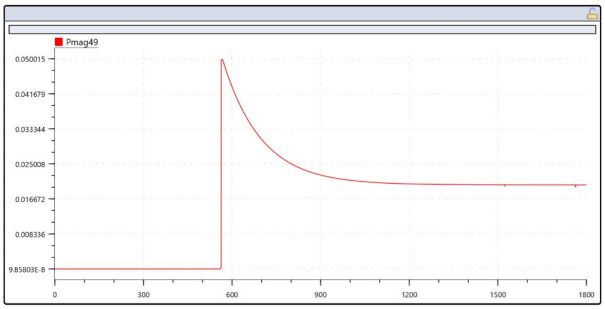
The optimization framework was applied to the IEEE 123-bus feeder consisting of 82 loads with a total base demand of 3.605 MW. After the optimization process, 42 loads were restored among the 82 loads on the 10 horizons. The total amount of load restored across the restoration horizons was 1.725 MW, representing approximately 47.8% of the total load demand. MATLAB created a switching sequence of loads based on the optimization, and measured different system parameters as well. Fig. 4 compares the MATLAB results of cumulative recovered base load power and the corresponding real power generation at the feeder end for each horizon. Due to the undiversified behavior of CLPU loads during restoration, a mismatch between the restored base load and the actual generation can be observed. However, this mismatch gradually reduced over time as the initially restored loads returned to their diversified state.

After completing the MATLAB portion of the co-simulation framework, the optimized switching sequence was transferred to RSCAD via socket communication. RSCAD then executed the real-time simulation of the service restoration process. During each restoration horizon, the designated loads were energized by switching on the loads, and their impact on the feeder end was observed. Although each horizon represented a 4-minute interval, the total simulation time was extended to 60 minutes (rather than the nominal 36 minutes) to allow the system to reach and display its steady-state operating conditions.

To investigate the CLPU characteristics at the individual load level, the current and power waveforms for Bus 49, energized during Horizon 2, are presented in Fig. 5. The load at this bus has a base demand of 0.02 MW and is supplied from a 2.4 kV node. As shown in the plots, immediately after the switching signal at approximately 550 seconds, both current and active power exhibit a sharp inrush peak, rising to



(a) Current at Bus 49



(b) Real power at Bus 49

Fig. 5: Real power and current of an energized bus (Bus 49)

nearly 2.5 times their eventual steady-state values, followed by a gradual exponential decay. This behavior reflects the undiversified nature of the load when first re-energized after an outage, where thermostatically controlled and motor-based components simultaneously draw high initial current. The curves indicate that the load reaches its steady operating condition after 1200 seconds, which is why the snapshot is illustrated over a 1800-second interval instead of the full 3600-second run time. The observed dynamic response confirms that the scheduler-driven delayed exponential load model in RSCAD accurately replicates CLPU behavior at the load level, providing a realistic foundation for system-level transient performance.

To evaluate the transient response of the system, the three-phase current and power waveforms at the feeder end were monitored in RSCAD. Fig. 6 shows the current in phases A, B, and C during the restoration process. In each horizon, a distinct current surge can be observed from the plot, which gradually decays in an exponential manner. Higher current peaks occur in later horizons when significantly larger load blocks are energized. The final current values for each phase was 329.33 A, 403.46 A and 401.41 A, respectively, whereas the maximum current was 395.7 A, 535.79 A and 496.62 A, respectively, which is around 1.3 times higher than the steady state values. If the feeder overcurrent relay were set based only on normal diversified loading, such transient peaks could cause unnecessary tripping during restoration, interrupting the blackstart process. To avoid this, a time-delayed or temporarily elevated pickup setting is typically required so the relay remains secure during the short inrush interval while still protecting against genuine faults. Incorporating adaptive

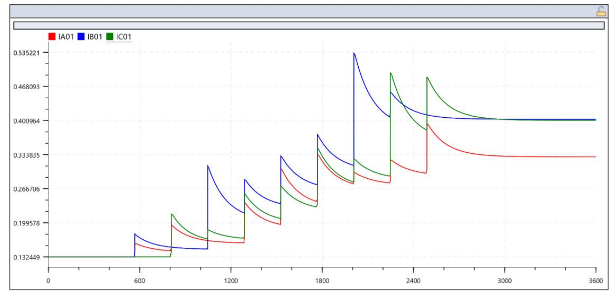


Fig. 6: Current of three phases at the feeder end

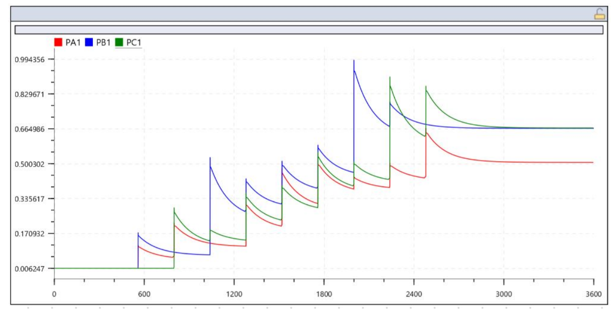


Fig. 7: Real power generation of three phases at the feeder end

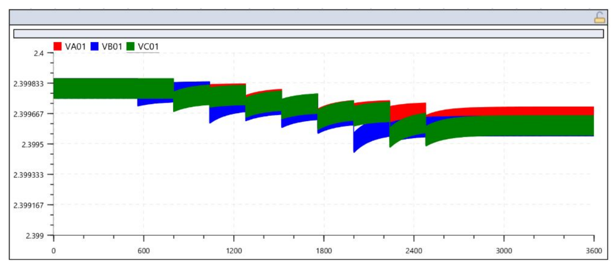


Fig. 8: Voltages of three phases at the feeder end

relay settings or coordinated restoration signalling can further prevent false operations and improve system reliability during blackstart restoration.

Similarly, the feeder-end real power waveforms in Fig. 7 exhibit a stepwise rise as additional loads are restored in each horizon. Each energization event produces a sharp increase in power demand, followed by a gradual decline toward a steady-state level as the previously energized loads transition from undiversified to diversified operating conditions. The peak real power value for each phase was 0.67325 MW, 0.99436 MW, and 0.91366 MW, respectively, whereas the steady-state values were 0.50585 MW, 0.66697 MW and 0.66850 MW, respectively. The figure also exhibits a progressive reduction of the overshoot amplitude in the later horizons, confirming that the staged restoration approach effectively manages system stress and prevents large deviations from stable operating limits.

In addition, the voltage at the feeder head was also monitored throughout the entire simulation, as shown in Fig. 8.

979-8-3315-8138-1

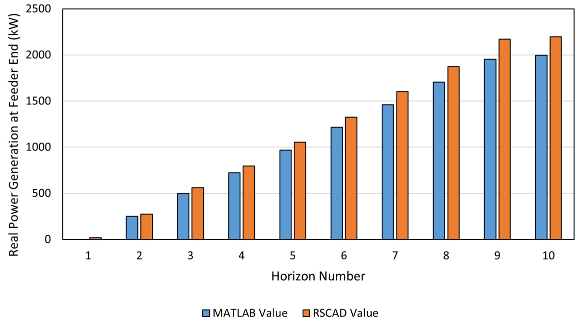


Fig. 9: Comparison between MATLAB result and RSCAD results of the real power generation

Each time a new group of loads was energized, a small voltage dip occurred due to the CLPU inrush, after which the voltage gradually recovered to its steady-state level. Although these dips are clearly visible, the voltage remained very close to the nominal 2.4 kV at all times and well within acceptable operating limits.

Fig. 9 compares the feeder-end real power generation calculated in MATLAB with the power measured in RSCAD for each horizon. The results show a strong consistency between the two environments. Although some mismatches can be observed between them, these are mostly due to the line losses, which were ignored during the optimization process. The deviations are much higher in the later horizons because a large part of the system was energized at that point, producing much more losses compared to the previous horizons. The steady state value of total real power generation is 1.841 MW, which is 6.72% higher than the diversified value of the total restored loads.

These outcomes demonstrate that the proposed co-simulation-based restoration framework can perfectly replicate the real-time sequential restoration while capturing the transient behavior of CLPU. However, some practical considerations must be acknowledged. First, the restoration strategy considered ideal switching operations without any protection systems, which can have an impact on the restoration process. Additionally, the current modeling uses a traditional modeling of the source instead of incorporating an inverter-based distributed energy resource (DER) model, which can significantly influence system dynamics at the restoration stage. The load model used in the restoration process addressed the standard CLPU response; however, using the same load model at each load may not fully represent real-world conditions. Despite these limitations, the proposed framework establishes a scalable foundation. Future work will focus on integrating DER-enabled microgrid restoration strategies, adaptive CLPU estimation, and protection coordination for more precise real-world scenarios.

IV. Conclusion

This paper presented a co-simulation-based service restoration framework that integrates optimization in MATLAB with a real-time simulation in RSCAD. The method uses a sequential load restoration while capturing the CLPU behavior observed during the restoration stage. The framework was applied to the IEEE-123 bus system, where 42 loads out of 82 loads can be restored in 10 horizons. The framework enables the evaluation of the system dynamics during the restoration process in RSCAD. The comparison between the MATLAB-generated results and the RSCAD simulation results shows a strong consistency, validating the restoration framework. Although the current work assumes some ideal scenarios, future works will address those limitations to further enhance the applicability of the approach in modern distribution networks.

Acknowledgment

This paper is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the under the Solar Energy Technologies (SETO) Office Fiscal Year 2020 Funding Program award number DE-EE0009337. The views expressed herein do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

References

[1] A. Heidari-Akhijahani and K. L. Butler-Purry, "A review on black-start service restoration of active distribution systems and microgrids," *Energies*, vol. 17, no. 1, 2024.

[2] B. Chen, C. Chen, J. Wang, and K. L. Butler-Purry, "Sequential service restoration for unbalanced distribution systems and microgrids," *IEEE Transactions on Power Systems*, vol. 33, no. 2, pp. 1507–1520, 2018.

[3] B. Chen, Z. Ye, C. Chen, and J. Wang, "Toward a milp modeling framework for distribution system restoration," *IEEE Transactions on Power Systems*, vol. 34, no. 3, pp. 1749–1760, 2019.

[4] M.-G. Choi, J.-H. Choi, S.-Y. Yun, and S.-J. Ahn, "Milp-based service restoration method utilizing both existing infrastructure and ders in active distribution networks," *IEEE Access*, vol. 10, pp. 36 477–36 489, 2022.

[5] J. Xiao, Y. Li, Y. Tan, C. Chen, Y. Cao, and K. Y. Lee, "A robust mixed-integer second-order cone programming for service restoration of distribution network," in *2018 IEEE Power & Energy Society General Meeting (PESGM)*, 2018, pp. 1–5.

[6] H. Wu, Y. Xie, Y. Xu, Q. Wu, C. Yu, and J. Sun, "Robust coordination of repair and dispatch resources for post-disaster service restoration of the distribution system," *International Journal of Electrical Power & Energy Systems*, vol. 136, p. 107611, 2022.

[7] S. Poudel and A. Dubey, "A two-stage service restoration method for electric power distribution systems," *IET Smart Grid*, vol. 4, no. 5, pp. 500–521, 2021.

[8] M. Song, R. R. nejad, and W. Sun, "Robust distribution system load restoration with time-dependent cold load pickup," *IEEE Transactions on Power Systems*, vol. 36, no. 4, pp. 3204–3215, 2021.

[9] IEEE Power and Energy Society, "Cold load pickup issues," IEEE Power and Energy Society, Technical Report PES-TR38, 2004.

[10] C. Hachmann, H. Becker, and M. Braun, "Cold load pickup model adequacy for power system restoration studies," *Energies*, vol. 15, no. 20, 2022.

[11] J. Wakileh and A. Pahwa, "Distribution system design optimization for cold load pickup," *IEEE Transactions on Power Systems*, vol. 11, no. 4, pp. 1879–1884, 1996.

[12] A. Alassi, Z. Feng, M. Syed, A. Egea-Alvarez, K. Ahmed, and G. Burt, "Distributed restart: Nonconventional blackstart resources: Rtds based network energization from grid forming converters: Part 2," 2022.

[13] N. Teklemariam, M. J. Hassan, B. Chowdhury, and R. Cox, "Blackstart optimization in islanded microgrids with varying types of load models," in *Proceedings of the 57th North American Power Symposium (NAPS)*, Hartford, Connecticut, USA, 2025, presented, to be published.