



A Multi-Stage Control Strategy for Transient Mitigation in Islanded Rural Mini-Grids via CCS-CNT Integration

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Abstract

Access to electricity remains limited in many rural communities in South Africa and other regions where grid extension is technically difficult and economically unattractive. In such settings, islandable minigrids offer a practical pathway for delivering reliable and sustainable electricity. This paper presents a novel staged islanding and reconnection control strategy for rural minigrids based on the coordinated operation of a Capacitor Coupled Substation (CCS) and a Controllable Network Transformer (CNT). The main contribution of the study is the integration of grid-status logic, a staged circuit-breaker switching sequence, and coordinated CCS-CNT control to reduce switching transients while maintaining voltage stability during the transition between grid-connected and islanded operation. The proposed method is evaluated on an 11 kV minigrid comprising a 1 MW solar photovoltaic source supplying a 500 kVA downstream load. A mathematical model and coordinated switching algorithm are developed and implemented in MATLAB/Simulink to represent the multi-stage breaker actions and the dynamic response of the CCS-CNT interface during islanding. In contrast to direct islanding, the proposed staged sequence is designed to mitigate inrush and synchronization transients, improve active and reactive power coordination, and keep voltage variations within acceptable utility limits. Simulation results show that the CCS-CNT-based staged control strategy improves voltage regulation and reduces transient disturbance during islanding events. These findings indicate that the proposed approach provides a robust and cost-effective solution for improving the resilience of rural minigrid power systems.

Subject Areas

Dynamical System

Keywords

Minigrid, Capacitor Coupled Substation, Controllable Network Transformer, Power Flow Control, Rural Electrification, System Modelling

1. Introduction

A vast number of communities in rural South Africa still have limited access to electricity, where access by grid extension is not feasible [1]. This is a common occurrence in other rural areas and is not limited to South Africa [2] [3]. Energy access is increasingly being delivered through grid-tied and off-grid infrastructure [4]. Mini-grids (MG) are one of the solutions for providing reliable and sustainable electricity to rural communities [5] [6]. Mini-grids can be defined as decentralized collective systems of electricity supply [7]. Islanded operation in mini-grids is critical for rural electrification, where access to a reliable grid connection is limited [8]. During high-impact events, the resilience of the islanded mini-grid ensures a sustainable power supply [9]. Along with grid extension and standalone systems, mini-grids are a crucial technical solution for delivering cost-effective, high-quality power to people in need of electricity access [10] [11]. In such systems, a Capacitor Coupled Substation (CCS), combined with a Controllable Network Transformer (CNT), can play a crucial role in managing load-supply balance and maintaining system stability during grid disconnection [12] [13]. The proposed model ensures minimal voltage fluctuations during the transition to an islanded state. While CCS and CNT are established technologies, their combined application using the proposed grid status function $G(t)$ for high-power rural tapping is a unique contribution that addresses the specific transient challenges of large-scale solar integration in isolated areas. This paper aims to provide an efficient strategy for controlling power flow and voltage stability in such islanded systems using mathematical modelling and algorithmic optimization.

Novelty of the Study

The primary novelty of this work, distinguishing it from previous CCS-CNT studies, lies not in the introduction of new hardware, but in the development of a coordinated staged-transition control strategy for rural islandable mini-grids. Specifically, this study integrates a grid-status logic function $G(t)$ with a time-sequenced, multi-stage circuit-breaker switching strategy to enable controlled islanding transitions.

Unlike earlier CCS-CNT research, which focused primarily on steady-state power flow, bidirectional control, and device-level operation, this work advances the framework to system-level transition control. The key contributions include: 1) the implementation of time-sequenced breaker operations to mitigate transient effects such as inrush and synchronization disturbances, 2) the incorporation of an autonomous grid-status logic $G(t)$ for real-time transition detection and

control, and 3) the application of the integrated strategy to a rural 1 MW PV-based minigrid under islanding conditions.

This combined approach enables improved transient suppression and voltage stabilization during disconnection from the main transmission grid, demonstrating the effectiveness of CCS-CNT systems in practical rural electrification scenarios.

2. System Configuration

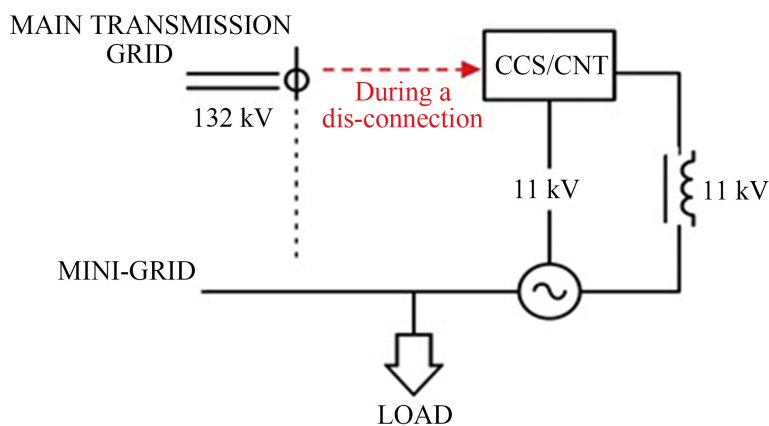
2.1. Mini-Grid Overview

Minigrids are self-sufficient electrical networks that supply power to connected loads using independent energy sources [14]. Decentralized projects powered by renewable energy could tap into this market's potential, positioning it as a major key driver for economic growth and prosperity [15]. This paper's proposed MG uses the following parameters:

- Power Source: A 1 MW solar photovoltaic (PV) system connected to an 11 kV MG.
- CCS: A CCS is designed to provide reactive power support during grid-connected operation and facilitate power transfer during an islanding scenario.
- CNT: CNT is integrated to adjust the voltage and current flow dynamically between the MG and the main transmission network at 132 kV.
- Load: The system is designed to support a downstream load of 500 kVA.

2.2. Electrical Layout

The minigrid is connected to the main transmission grid via a CCS-CNT. The transmission grid operates at 132 kV, while the minigrid operates at 11 kV. During a grid disconnection event (islanding), the CCS and CNT provide the necessary adjustments to maintain a stable power supply to the load. A simplified electrical layout is given in **Figure 1**.



During a grid dis-connection event (islanding), the CCS and CNT provide the necessary adjustments to maintain a stable power supply to the load.

Figure 1. Electrical layout.

2.3. MATLAB/Simulink Model and Parameterization

The command and descriptive activities of the MATLAB/Simulink model for the control system design for microgrid islanding and reconnection sequence is presented in **Table 1**.

Table 1. Control system design for microgrid islanding and reconnection.

1. Components Needed	
<ul style="list-style-type: none"> • Voltage Monitoring Unit (VMU): Detects voltage status on the transmission line. • Microgrid Controller (MGC): Decides when to island or reconnect. • CNT with Fast Switching Capability: Controls power flow and ensures smooth transition. • Synchronization Unit (SU): Checks phase, frequency, and voltage before reconnecting. 	
2. Operation Modes	
(a) Normal Mode (Connected to the Grid)	
<ul style="list-style-type: none"> • Transmission line is active (voltage present). • The microgrid supplies local loads, but power flows bidirectionally if needed. • CNT regulates voltage and power. 	
(b) Islanding Mode (Transmission Line Voltage Lost)	
<ul style="list-style-type: none"> • The VMU detects a loss of voltage. • The Microgrid Controller (MGC) signals the CNT to switch to island mode. • The microgrid takes over and supplies the downstream load. • Local generation sources (solar PV) adjust power to match the load. 	
(c) Reconnection Mode (Transmission Line Voltage Restored)	
<ul style="list-style-type: none"> • The VMU detects that the transmission line voltage is back. • The Synchronization Unit (SU) checks: <ul style="list-style-type: none"> ○ Voltage magnitude matching ○ Frequency synchronization ○ Phase alignment • Once the conditions are met, the CNT gradually reconnects the microgrid to the main grid. • CNT smoothly transitions back to normal operation. 	
3. Control Logic Flowchart	
(a) Check Transmission Line Voltage	
<ul style="list-style-type: none"> ○ If Voltage = 0 V → Islanding Mode ○ If Voltage Restored → Go to Step (b) 	
(b) Check Synchronization Conditions	
<ul style="list-style-type: none"> ○ If Voltage, Frequency, and Phase Match → Proceed to Step © ○ If Mismatch Detected → Wait and Adjust 	
(c) Reconnect CNT to the Grid	
<ul style="list-style-type: none"> ○ CNT switches back to grid-connected mode. ○ Power sharing between microgrid and main grid resumes. 	
4. Protection & Stability Considerations	
<ul style="list-style-type: none"> • Anti-Islanding Protection: Ensures unintentional islanding does not occur. • Soft Switching: Prevents sudden inrush currents during reconnection. • Fault Handling: If faults are detected, the system delays reconnection. • Energy Management Mechanisms: Helps maintain stability when islanded. 	
This system ensures seamless transition between grid-connected and islanded modes, preventing blackouts and improving reliability.	

A MATLAB/Simulink model is developed with the following components:

- **Main Transmission Grid (132 kV):** Represented by a three-phase voltage source.
- **Capacitor Coupled Substation (CCS):** Modelled using a capacitor bank and transformer.
- **Controllable Network Transformer (CNT):** A three-phase transformer with control logic for voltage regulation.
- **Mini-Grid (11 kV):** A separate distribution network supplying local loads.
- **Circuit Breaker for Islanding:** A switching mechanism to disconnect the main grid.
- **Control System:** Implements voltage and frequency regulation during islanding.

The models are presented in **Figure 2**.

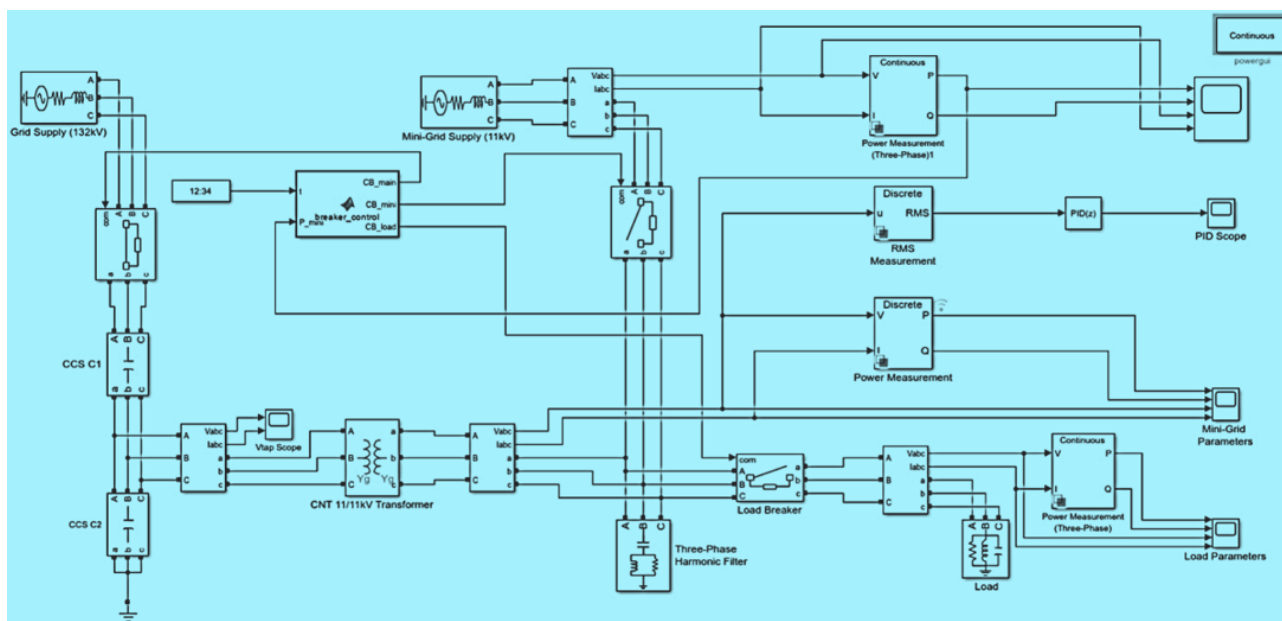


Figure 2. MATLAB/Simulink model with circuit breaker logic controller.

2.4. Simulation Parameters

Table 2. Simulation parameters.

Parameter	Value/Description
PV system rating	1 MW
PV model	Averaged inverter (controlled current source)
Load rating	500 kVA
Load type	Constant PQ (three-phase)
Power factor	0.8 (lagging)
Main grid transformer	132/11 kV
CNT rating	MVA-rated (matched to mini-grid interface)

Continued

CCS transformer	11 kV/400V
Control method	Proportional control
Control gain	K_p
Grid-status function	$G(t)$
Islanding threshold	$V < 0.1$ pu
Solver type	Continuous (ode45/ode23tb)
Sampling time	50 μ s (1×10^{-4} s)
Breaker model	Ideal circuit breakers
Switching strategy	Time-sequenced staged switching
Voltage deviation limit	$\pm 5\%$

A standardized set of simulation parameters was adopted to ensure reproducibility and consistency of the CCS-CNT model. The system was implemented in MATLAB/Simulink using an averaged representation of the PV source, a constant PQ load model, and coordinated CNT control under defined islanding conditions. Key electrical ratings, control settings, solver configuration, and performance thresholds are summarized in **Table 2**.

Overall, the simulation framework integrates detailed system ratings, control parameters, solver configuration, and islanding logic to ensure that results are reproducible and reflective of practical rural mini-grid operating conditions.

3. Mathematical Representation

3.1. Power Flow Equation

The power flow in the system can be expressed using the following equations.

3.1.1. Active Power (P)

$$P_{load} = P_{solar} + P_{CCS} - P_{CNT}$$

where:

P_{load} is the load power.

P_{solar} is the power generated by the solar system.

P_{CCS} is the power provided by the CCS during islanding.

P_{CNT} is the power adjusted by the CNT for voltage regulation.

3.1.2. Reactive Power (Q)

$$Q_{load} = Q_{solar} + Q_{CCS} - Q_{CNT}$$

where:

Q_{load} is the reactive power of the load.

Q_{solar} is the reactive power contribution from the solar system.

Q_{CCS} is the reactive power adjustment provided by the CCS during islanding.

Q_{CNT} is the reactive power control provided by the CNT.

3.2. Voltage Regulation

The voltage (V_{CCS}) at the CCS is regulated by the CNT in response to the grid disconnection, ensuring that voltage fluctuations do not exceed permissible limits:

$$V_{CCS} = V_{ref} \pm \Delta V$$

where:

V_{ref} is the reference voltage.

ΔV is the permissible voltage fluctuation.

4. Algorithm for Power Flow Control

To efficiently control the power flow during islanding, an algorithm is proposed to balance the active and reactive power across the CCS and CNT while ensuring voltage stability.

4.1. Power Flow Equations

When the grid is connected, power flows from the 132 kV transmission grid to the 11 kV minigrid through the CCS and CNT:

- Power Flow through the CCS:

$$P_{CCS} = V_{HV} \times I_{CCS} \times \cos \theta_{CCS}$$

where:

V_{HV} = 132 kV (voltage at the high voltage side of the CCS).

I_{CCS} is the current flowing through the CCS.

θ_{CCS} is the phase angle between the voltage and current at the CCS.

- Power Conversion by CCS:

$$P_{MiniGrid} = V_{LV} \times I_{MiniGrid} \times \cos(\theta_{MiniGrid})$$

where:

V_{LV} = 11 kV (tapped voltage), $I_{MiniGrid}$ is the current delivered to the mini-grid, and $\theta_{MiniGrid}$ is the phase angle at the mini-grid side.

4.2. Mathematical Representation for the Proposed Power Flow Control Algorithm

- *Monitor Power Flow*

At any given time, measure the active and reactive power at load, CCS, and CNT:

$$P_{load}, Q_{load}, Q_{CCS}, P_{CNT}, Q_{CNT}$$

Ensure that the power balance is maintained:

$$P_{CCS} + P_{CNT} = P_{load}$$

$$Q_{CCS} + Q_{CNT} = Q_{load}$$

- *Grid Disconnection*

Define a grid status function $G(t)$:

$$G(t) = \begin{cases} 1, & \text{Grid connected} \\ 0, & \text{Grid disconnected} \end{cases}$$

where:

$G(t) = 0$, activate the CCS and CNT to maintain power balance:

$$P_{CCS} + P_{CNT} = P_{load}$$

$$Q_{CCS} + Q_{CNT} = Q_{load}$$

- *Adjust CNT Settings*

The CNT regulates the voltage (V_{CNT}) and current (I_{CNT}) dynamically:

$$V_{CNT}(t) = V_{Load}(t) \pm \Delta V$$

$$I_{CNT}(t) = \frac{P_{Load} + jQ_{Load}}{V_{Load}}$$

- *Optimize Reactive Power*

The CCS provides reactive power support, while the CNT adjusts to voltage regulation demands:

$$Q_{CCS} = Q_{Load} - Q_{CNT}$$

$$V_{CCS} = V_{Load} \pm \Delta V$$

- *Voltage Stability Check*

Ensure voltage at the load, and CCS does not exceed allowed deviation limits:

$$V_{min} \leq V_{Load}, V_{CCS} \leq V_{max}$$

If V_{CCS} or V_{Load} exceeds limits, adjust CNT settings:

$$V_{CNT} = V_{CNT} - k(\Delta V)$$

where k is a proportional gain to maintain stability.

This mathematical representation ensures the CNT and CCS settings during islanding conditions.

4.3. Operational Philosophy and Sequence of Operations

The modelled system outlines a sequence of operations where the main grid and a minigrid operate in parallel to supply a specified load. The circuit breakers (CBs) switch at various times, as in **Table 3**. The sequence is designed as a staged transition test to isolate inrush, synchronization, reconnection, and final islanding transients.

Table 3. System switching transaction.

Time (s)	Event	Effect on system
0.8	Load CB closes	The load is connected to the main grid.
0.91	Mini-grid CB closes	Minigrid momentarily connects.
0.95	Mini-grid CB opens	Minigrid disconnects again.
0.99	Mini-grid CB closes	Minigrid connects permanently.
1.1	Main grid CB opens	Minigrid becomes the sole power source.

This sequence of operation is also mathematically represented in a power flow condition as follows:

- Before 0.8 s: No power flow.
- 0.8 s - 0.91 s: Main grid supplies full load.
- 0.91 s - 0.95 s: Both grids momentarily operate in parallel.
- 0.95 s - 0.99 s: Only the main grid supplies power again.
- 0.99 s - 1.1 s: Both grids supply power.
- After 1.1 s: Only the mini-grid supplies power.

When both grids are supplying power (at 0.99 s - 1.1 s), power-sharing rules (e.g., droop control) would determine $P_{MG}(t)$ and $P_{mG}(t)$ where the power contribution from each source depends on the CB states:

$$P_{MG}(t) = P_L(t) \times S_{MG}(t)$$

$$P_{mG}(t) = P_L(t) \times S_{mG}(t)$$

The states are being extrapolated from the following variables and notations:

$S_{MG}(t)$ = Main Grid CB state (1 = Closed, 0 = Open)

$S_{mG}(t)$ = Mini-Grid CB state (1 = Closed, 0 = Open)

$S_L(t)$ = Load CB state (1 = Closed, 0 = Open)

$P_{MG}(t)$ = Power supplied by the main grid

$P_{mG}(t)$ = Power supplied by the mini-grid

$P_L(t)$ = Power consumed by the load

And:

$$P_L(t) = P_{MG}(t) + P_{mG}(t)$$

The CB state equations are given by:

$$S_L(t) = \begin{cases} 0, & t < 0.8 \\ 1, & t \geq 0.8 \end{cases}$$

$$S_{mG}(t) = \begin{cases} 0, & t < 0.91 \\ 1, & 0.91 \leq t < 0.95 \\ 0, & 0.95 \leq t < 0.99 \\ 1, & t \geq 0.99 \end{cases}$$

$$S_{MG}(t) = \begin{cases} 1, & t < 1.1 \\ 0, & t \geq 1.1 \end{cases}$$

Switching Times Rationale

The selected switching instants at 0.8 s, 0.91 s, 0.95 s, 0.99 s, and 1.1 s were designed to represent a controlled, staged operational sequence rather than arbitrary breaker events. This timing structure serves as a transient test framework to evaluate system stability under progressively changing network conditions, leading to full islanding.

Specifically, the switching sequence is organized as follows: at 0.8 s, the load is connected to establish a steady-state discrete times for the system; between 0.91 s and 0.99 s, a series of short-duration switching events are introduced to emulate temporary synchronization and desynchronization of the mini-grid, enabling the assessment of transient responses under partial grid interaction; and at 1.1 s, the

final switching action initiates intentional islanding, where the mini-grid transitions to fully autonomous operation.

The spacing between these events was deliberately chosen to isolate the dominant transient phenomena associated with each stage, including inrush currents, synchronization disturbances, and voltage fluctuations. This staged approach allows the impact of each switching action to be observed independently while preserving a realistic transition pathway from grid-connected to islanded operation.

Overall, the sequence provides a systematic means to evaluate transient suppression capability, synchronization stability, and the effectiveness of the proposed control strategy during the transition to islanded operation.

5. Results

The results presented the observation of the modelled system during the islanding scenario. The main focus of this study is the observation of the main voltage deviations at the load during islanding. The results are in **Figure 3**.

	Value	Time
Max	1.661e+04	1.037
Min	-1.674e+04	1.006
Peak to Peak	3.335e+04	
Mean	-5.501e+02	
Median	-8.743e+02	
RMS	1.137e+04	

Figure 3. CCS red phase voltage signal statistics.

The model results presented in **Figure 3** show the tapped voltage at 1.137×10^4 V, which is the desired V_{tap} . The RMS value of 1.137×10^4 V shown in **Figure 3** represents the stabilized tapped voltage. This confirms that the control system maintains the voltage within the standard $\pm 5\%$ permissible fluctuation limits ΔV required by utility reference standards, ensuring equipment safety during the 1.1 s islanding event.

This result is further presented in a waveform in **Figure 4**.

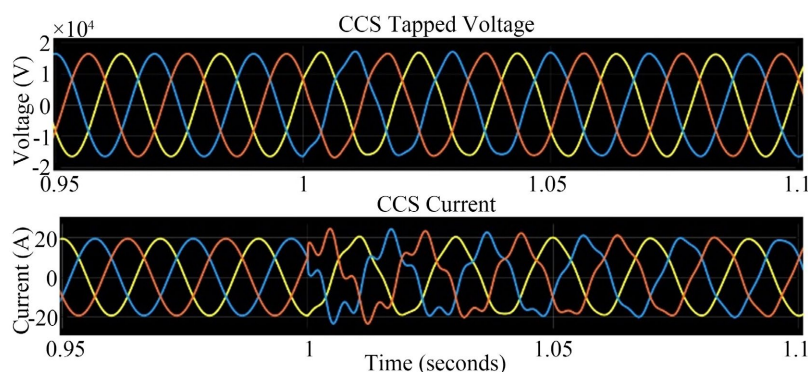


Figure 4. CCS Voltage: Load switched at 1 second.

The resulting transients during switching are given by:

When:

- Load CB closes at 0.8 s, the resulting transient effect of inrush current is given by:

$$i(t) = I_{final} (1 - e^{-t/\tau})$$

- Mini-grid CB closes at 0.91 s, resulting in synchronization transient given as:

$$i(t) = \frac{V_{MG} - V_{mG}}{Z_{eq}} (1 - e^{-t/\tau})$$

- Minigrid CB opens at 0.95 s, resulting in power fluctuations given by:

$$\Delta P = P_{MG} - P_{mG}$$

- Minigrid CB closes at 0.99 s, resulting in a residual charge transient given by:

$$V_{mG}(t) = V_{final} + V_{transient} e^{-\alpha t} \cos(\omega_d t + \phi)$$

When the main grid CB opens at 1.1 s (shown in **Figure 5**), there is a transient effect resulting from a power dip and frequency shift, and given by:

$$\Delta P = P_{MG} - P_{mG}$$

where:

$I_{steady-state}$ = Final steady-state current

$I_{transient}$ = Initial transient current

$\alpha = \frac{R}{2L}$ = Damping factor

$\omega_d = \sqrt{\frac{1}{LC} - \alpha^2}$ = Damped natural frequency

ϕ = Phase angle

The Grid Control System (GCS) is achieved by implementing a GCS that uses control logic for the CB operations.

A State flow or MATLAB Function Block can be used for CB operations. The state definition on the state flow or the MATLAB Function Block is as presented in **Table 4**.

Table 4. State definitions in state flow.

State	Condition	Action
Main grid closed	$t < 1.1$ s	Main grid supplies power
Main grid opens	$t \geq 1.1$ s	Main grid breaker opens
Mini-grid closed	$t = 0.91$ s, 0.99 s	Minigrid starts supplying power
Mini-grid opens	$t = 0.95$ s	Minigrid temporarily disconnects
Load breaker closed	$t \geq 0.8$ s	Load breaker is closed
Load disconnected	$P_{mini-grid} = 0$ after 1.1 s	Load breaker opens

When using MATLAB Block Functions, the CB operation is based in time and power availability. The logic is as follows (See **Table 5**):

Table 5. CB Logic using MATLAB Function Block

```
function [CB_main, CB_mini, CB_load] = breaker_control(t, P_mini)
% Breaker control logic for Simulink model
% Inputs:
% t - Current simulation time (s)
% P_mini - Power from the mini-grid (MW)
% Outputs:
% CB_main - Main grid breaker status (1 = Closed, 0 = Open)
% CB_mini - Mini-grid breaker status (1 = Closed, 0 = Open)
% CB_load - Load breaker status (1 = Closed, 0 = Open)
% Initialize all breakers
CB_main = 1; % Main grid starts closed
CB_mini = 0; % Mini-grid starts open
CB_load = 0; % Load starts open
% Load breaker closes at 0.8 s
if t >= 0.8
    CB_load = 1;
end
% Mini-grid operations
if t >= 0.91 && t < 0.95
    CB_mini = 1; % Mini-grid closes at 0.91 s
elseif t >= 0.95 && t < 0.99
    CB_mini = 0; % Mini-grid opens at 0.95 s
elseif t >= 0.99
    CB_mini = 1; % Mini-grid closes again at 0.99 s
end
% Main grid breaker opens at 1.1 s
if t >= 1.1
    CB_main = 0; % Main grid disconnects
end
% If no power from mini-grid after 1.1 s, open the load breaker
if t >= 1.1 && all(P_mini == 0)
    CB_load = 0; % Load disconnects due to no power
end
end
```

The final sequence results in the expected system behaviour as presented in **Table 6**.

Table 6. Simulation and expected behaviour.

Time (s)	Action
0.8	Load breaker closes
0.91	Mini-grid breaker closes
0.95	Mini-grid breaker opens
0.99	Mini-grid breaker closes again
1.1	Main grid breaker opens
>1.1 & $P_{mini} = 0$	Load breaker opens (if no power from minigrid)

With the mathematics representation given as:

- Main Grid Breaker:

$$CB_{main}(t) = \begin{cases} 1, & \text{if } t < 1.1 \\ 0, & \text{if } t \geq 1.1 \end{cases}$$

- Mini-Grid Breaker:

$$CB_{mini}(t) = \begin{cases} 0, & \text{if } t < 0.9 \\ 1, & \text{if } 0.91 \leq t < 0.95 \\ 0, & \text{if } 0.95 \leq t < 0.99 \\ 1, & \text{if } t \geq 0.99 \end{cases}$$

- Load Breaker:

$$CB_{load}(t, P_{mini}(t)) = \begin{cases} 0, & \text{if } t < 0.8 \\ 1, & \text{if } 0.8 \leq t < 1.1, P_{mini}(t) > 0 \\ 0, & \text{if } t \geq 1.1, P_{mini}(t) = 0 \\ 1, & \text{if } 0.8 \leq t < 1.1, P_{mini}(t) \text{ continues to be active} \end{cases}$$

The voltage measurements are given by **Figures 4-12**.

Time (seconds)	Value
1 1.053	1.101e+04
2 1.125	-8.083e+03
ΔT 71.646 ms	ΔY 1.909e+04
1 / ΔT	13.957 Hz
$\Delta Y / \Delta T$	266.478 (/ms)

Figure 5. Load voltage measurement.

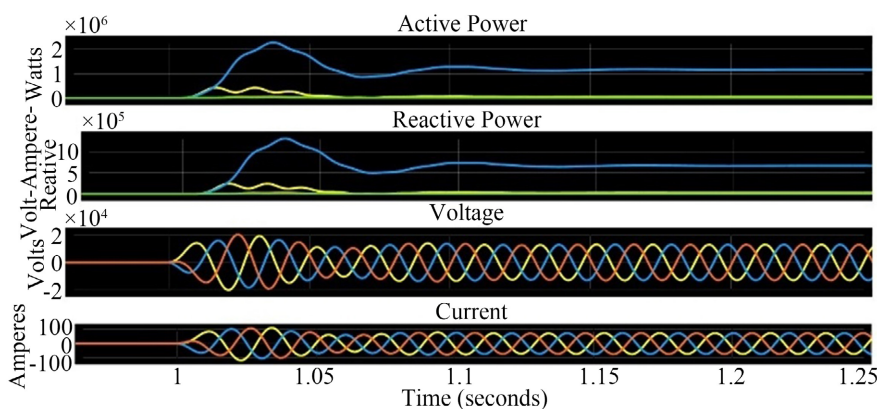


Figure 6. Load parameters: MG supplying power.

Where each figure representation is:

- **Figure 5:** The voltage measured at the load.
- **Figure 6:** Graphical representation when MG supplies power.
- **Figure 7:** Load voltage when the MG supplies zero power.
- **Figure 8:** Graphical representation of **Figure 8**.

- **Figure 9:** MG when zero power is generated.
- **Figure 10:** MG when power is generated.
- **Figure 11:** MG voltage when power is generated.
- **Figure 12:** Base Tapped voltage when CCS is used.

Measurements			
	Time (seconds)	Value	
1	1.063	2.228e+01	
2	1.178	5.190e+00	
ΔT	115.905 ms	ΔY	1.709e+01
$1 / \Delta T$		8.628 Hz	
$\Delta Y / \Delta T$		147.488 (/s)	

Figure 7. Load parameters when no MG supply.

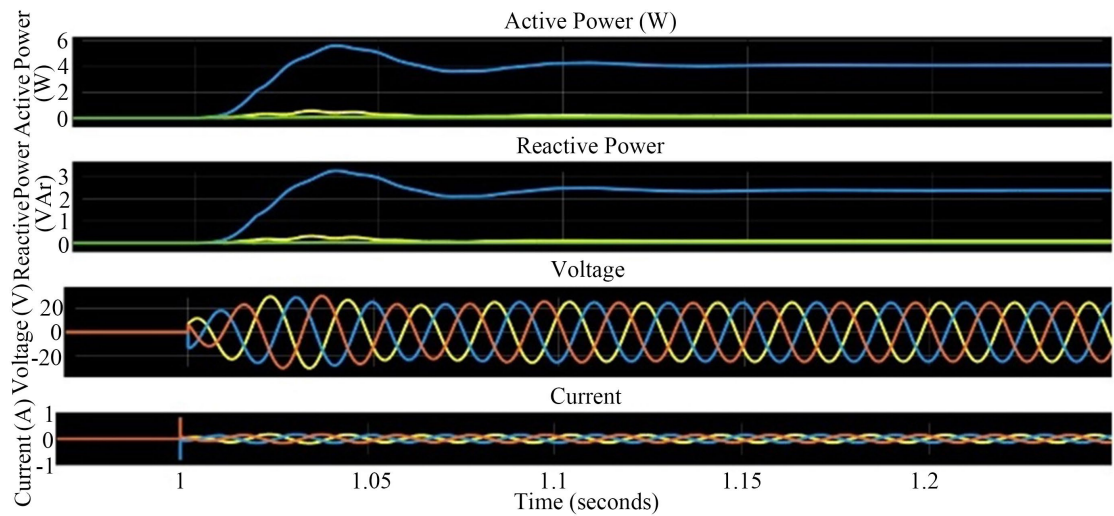


Figure 8. Load parameters when no MG power.

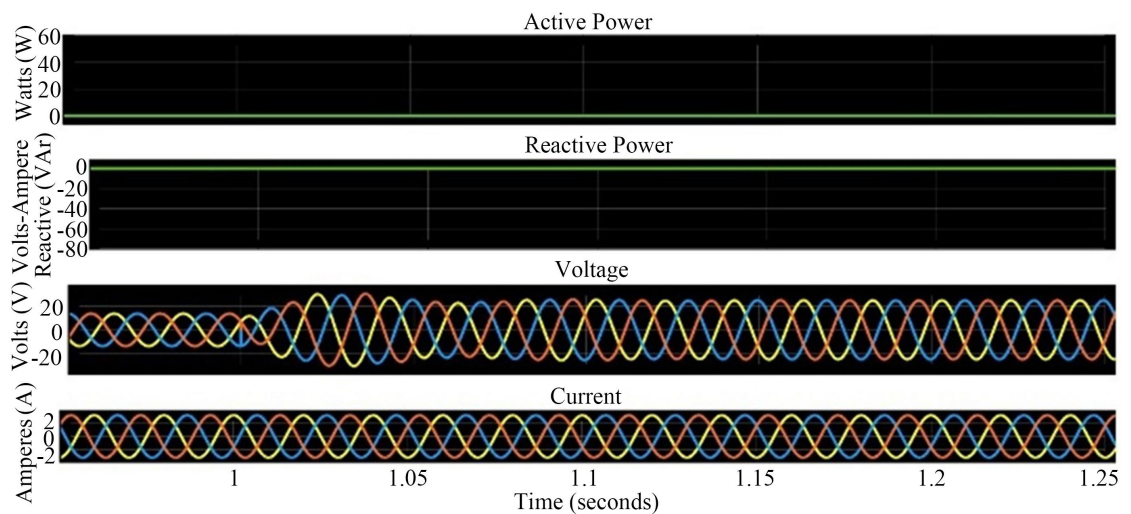


Figure 9. Mini-grid parameters with no generation.

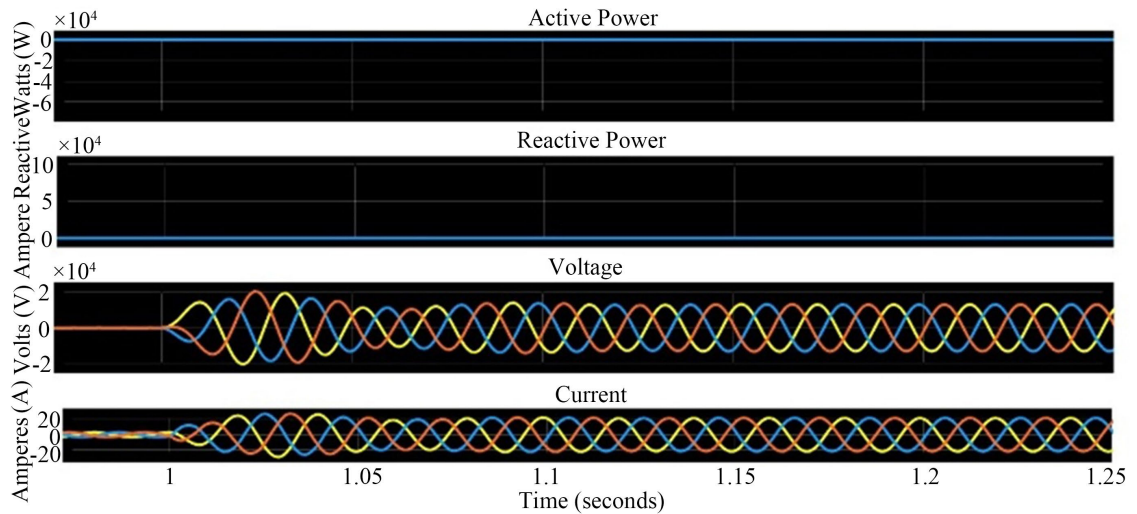


Figure 10. MG when generating.

Measurements	
Time (seconds)	Value
1 1.053	1.189e+04
2 1.132	1.350e+04
ΔT 79.211 ms	ΔY 1.604e+03
<hr/>	
1 / ΔT	12.624 Hz
$\Delta Y / \Delta T$	20.244 (/ms)

Figure 11. MG voltage.

Measurements	
Time (seconds)	Value
1 1.053	1.189e+04
2 1.132	1.350e+04
ΔT 79.211 ms	ΔY 1.604e+03
<hr/>	
1 / ΔT	12.624 Hz
$\Delta Y / \Delta T$	20.244 (/ms)

Figure 12. Tapped voltage.

6. Discussion

The transient phenomena identified throughout the simulation reflect the critical nature of load management during the islanding process. When the load CB closes at 0.8 seconds, a significant inrush current is generated as expected, characterized by the exponential rise defined by the function:

$$i(t) = I_{final} (1 - e^{-t/\tau})$$

This inrush can lead to temporary voltage fluctuations that may impact sensitive electrical equipment. The observations during the minigrd operations (with

CB closing and opening at 0.91 s, 0.95 s, and again at 0.99 s) highlight the importance of synchronization in maintaining stable voltage levels. The synchronization transient, captured by:

$$i(t) = \frac{V_{MG} - V_{mG}}{Z_{eq}} (1 - e^{-t/\tau}),$$

Indicates that careful control of the minigrid's output is necessary to prevent abrupt voltage shifts, which could destabilize the entire system. These transients need to be considered in the design of control strategies that enforce a seamless transition into and out of islanding operation. Additionally, the significant effects of power fluctuations when the minigrid CB opens at 0.95 s highlight the necessity for robust energy management strategies. In the absence of power from the minigrid, the subsequent drop in system stability must be adequately addressed by reactive power support or by strategically designed energy storage systems. The Grid Control System (GCS), executed through MATLAB function blocks and state flow diagrams, is integral in coordinating the dynamic response of the system. The use of state definitions for managing the main grid and minigrid breakers ensures systematic operations, which are critical during the transition states. The control logic effectively allows for the necessary responses to changes in the electrical environment, such as disconnecting the load in scenarios of no minigrid generation after 1.1 seconds. The results from the CB logic reveal the robustness of the control algorithms, providing a foundation for automating responses based on power availability and operational conditions. However, future improvements could include real-time analytics and machine learning techniques to enhance predictive capabilities, thus minimizing delays during critical events. The data portrayed in **Figures 4-12** shed light on system stability under varying operational conditions. When the minigrid supplies power, the load parameters show stable voltage levels, indicative of successful integration with the existing grid structure. Conversely, the parameters under conditions of no supply show the changes in load behaviour, emphasizing the uncertain balance that occurs during islanding. The simulated transient behaviours, such as the inrush current, align with the theoretical bidirectional power flow models established in [12] and [13], providing indirect validation of the simulation's accuracy in the absence of site-specific field data. Although this study utilizes a static 500 kVA load, the control algorithm incorporates a proportional gain k in the CNT adjustment formula $V_{CNT} = V_{CNT} - k(\Delta V)$ to ensure the system's robustness against varying load demands.

7. Conclusion

This study provides important insights into microgrid behaviour under islanding conditions, with particular emphasis on voltage stability and control system performance. The simulation results highlight the dynamics of load voltage deviation during the transition from grid-connected to islanded operation. Overall, the findings demonstrate the need for improved control strategies, continuous system

monitoring, and proactive energy management to enhance system resilience. Increasing the monitoring resolution and appropriately tuning system time constants may further reduce adverse transient effects on the load. The use of MATLAB function blocks also supports model flexibility, allowing for easier modification and scalability in future studies. Further research is required to deepen the understanding of these transient dynamics and to optimize control strategies for more advanced grid configurations. In addition, the integration of advanced voltage regulation methods, CCS-CNT systems, and smart grid technologies, such as automatic voltage regulators, predictive load forecasting, and real-time communication between grid components, is recommended to further improve voltage stability and system robustness during islanding.

Conflicts of Interest

The author declares no conflicts of interest.

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