Scientific Research Publishing

Journal of Power and Energy Engineering, 2023, 11, 1-14
https://www.scirp.org/journal/jpee
ISSN Online: 2327-5901
ISSN Print: 2327-588X

Modeling and Simulation of a Transmission Line Response to a 400 kV/400V Capacitor Coupled Substation

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How to cite this paper: Nene, S.W., Abe, B.T. and Nnachi, A.F. (2023) Modeling and Simulation of a Transmission Line Response to a 400 kV/400V Capacitor Coupled Substation. *Journal of Power and Energy Engineering*, **11**, 1-14.
https://doi.org/10.4236/jpee.2023.1112001

Received: September 27, 2023
Accepted: December 9, 2023
Published: December 12, 2023

Abstract

The access to electricity in rural areas is extremely limited, but it is crucial for all citizens. The population in rural areas of sub-Saharan African (SSA) countries is generally low, making it economically unfeasible to implement traditional rural electrification (CRE) projects due to the high cost of establishing the necessary distribution infrastructure. To address this cost issue, one alternative technology for rural electrification (URE) that can be explored is the Capacitor Coupled Substation (CCS) technology. CCS is a cost-effective solution for supplying electricity to rural areas. The research is necessitated by the need to offer a cost-effective technology for supplying electricity to sparsely populated communities. This paper examines the impact on the transmission network when a 400 kV/400V CCS is connected to it. The system response when a CCS is connected to the network was modeled using MATLAB/Simulink. The results, based on the fixed load of 80 kW, showed negligible interference on the transmission line voltage. However, there was minor impact on the parameters downstream of the tapping point. These findings were further supported by introducing a fault condition to the CCS, which showed that interferences with the CCS could affect the overall stability of the transmission network downstream of the tapping node, similar to the behavior of an unstable load.

Keywords

Capacitor Coupled Substation, Conventional Rural Electrification, Unconventional Rural Electrification, Transmission Line Behavior, Power System Simulation

1. Introduction

Electricity plays a crucial role in the economic development of any developing country. In Sub-Saharan African countries (SSA), there are still numerous rural communities that have limited access to electricity [1]. Due to the widely dispersed load and the high cost of infrastructure development, it is not economically feasible to construct traditional distribution networks in these areas [2]. Therefore, alternative technologies such as Capacitor Coupled Substations (CCS) need to be explored.

CCS is a technology that utilizes capacitors to extract power from high voltage (HV) lines and distribute it at a lower voltage level, providing an affordable electricity solution for sparsely populated communities [3]. However, direct tapping of electrical power from HV transmission lines using capacitors can lead to transient behavior, which can have negative effects on the components of the CCS [4]. Starting from the 1990s, research studies have consistently shown that incorporating passive dampers enhances the stability of a CCS [5]. The majority of these studies have primarily concentrated on investigating the advantages of using a CCS to tap power from the HV System [4] [6] [7]. The main research questions to be answered are:

1) Is there any notable impact on the main electrical transmission network if a CCS is connected to it?

2) Can a 400 V network be tapped off directly from a 400 kV through a CCS?

2. Problem Statement

Electricity is classified as a basic necessity. Communities in sparsely populated areas still have limited access to electricity due, partly, to the cost related to the construction of a conventional rural electrification distribution network. Therefore, other cost-effective technologies need to be explored. This paper, therefore, is necessitated by need to analyze if a CCS is one of the technologies that can be used to supply electricity to sparsely populated areas. Furthermore, the proposed CCS-CNT can be used for two different applications, *i.e.*, bi-direction power flow control to allow micro-grids connection to the main transmission line, and the CNT can function as a ferroresonance suppression circuit.

3. Background

Existing literature highlights that a CCS is a cost-effective technology that can be utilized to provide electricity to rural communities located in close proximity to high voltage lines [6] [8]. One of the advantages of implementing a CCS is that when it is positioned between two inductive substations, it functions as a reactive compensator, thereby enhancing the voltage regulation of the line [9]. CCS can play a significant role in distributing electricity at medium voltage levels, allowing sparsely populated rural areas to access electrical power via overhead HV transmission lines through the implementation of a CCS. This research paper presents the findings of the impact on the network, particularly the transmission line voltage, upon the connection of a CCS. However, the downstream network was not thoroughly analyzed by considering its individual parameters that contribute to the overall stability of the system.

This paper makes an original contribution by examining the effects of a CCS on a transmission network, with a specific focus on the supply voltage. It serves as a foundation for understanding the behavior of a proposed hybridized Capacitor Couple Substation with a Controllable Network Transformer (CCS-CNT) when integrated into an existing electrical transmission network for power tapping and injection into the transmission network. This paper further contributes to the knowledge in the field of unconventional rural electrification and micro-grids embedment using a CCS-CNT system. The CCS-CNT can also be used as a power flow controller within an electrical network. This is due to the fact that a CNT can sense variations in the incoming voltage and make real-time adjustments to ensure that the output voltage is within the desired range. This could also eliminate some key challenges related to the impacts of distribution systems of large-scale solar photovoltaic integration. Some of these challenges are the inrush current, unexpected islanding, overvoltage, power output fluctuation and harmonics [10].

The following sub-sections summarize a CCS.

3.1. Capacitor Coupled Substation

A CCS operates on the same principle as the Capacitive Voltage Transformer (CVT) [11]. In reference [12], a CVT is described as a transformer that reduces high voltage (HV) signals to low voltage (LV) signals, which are used for metering and operating protective relays. The design of a CVT includes a capacitive divider with an insulating cylinder, as well as an electromagnetic unit that consists of a step-down transformer, a compensation reactor, and a damper, as depicted in **Figure 1** below [13] [14].

Similarly, the CCS uses capacitors to lower the high voltage from the HV transmission lines to a medium voltage level. **Figure 2** below shows a diagram of an overly simplified CCS.

Figure 2 above presents a simplified CCS with capacitors (C_1 and C_2) and a capacitor divider connected across the incoming voltage (V_{in}) supplying the desired tap-voltage (V_T) measured from the tapping node between the two capacitors. The output voltage (Vout) is the difference between V_T and the voltage drop across the inductor (L). C_1 and C_2 are a representation of capacitor banks rather than individual capacitors where C_1 represents Capacitor Bank 1 and C_2

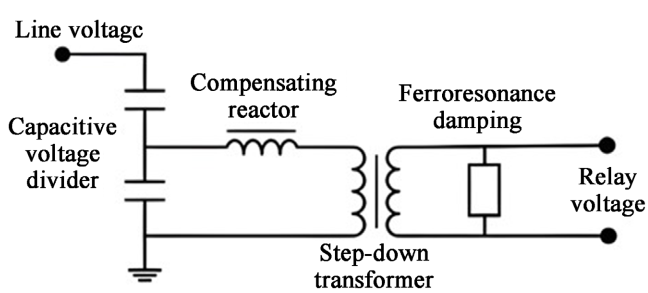

Figure 1. Simplified CVT [14].

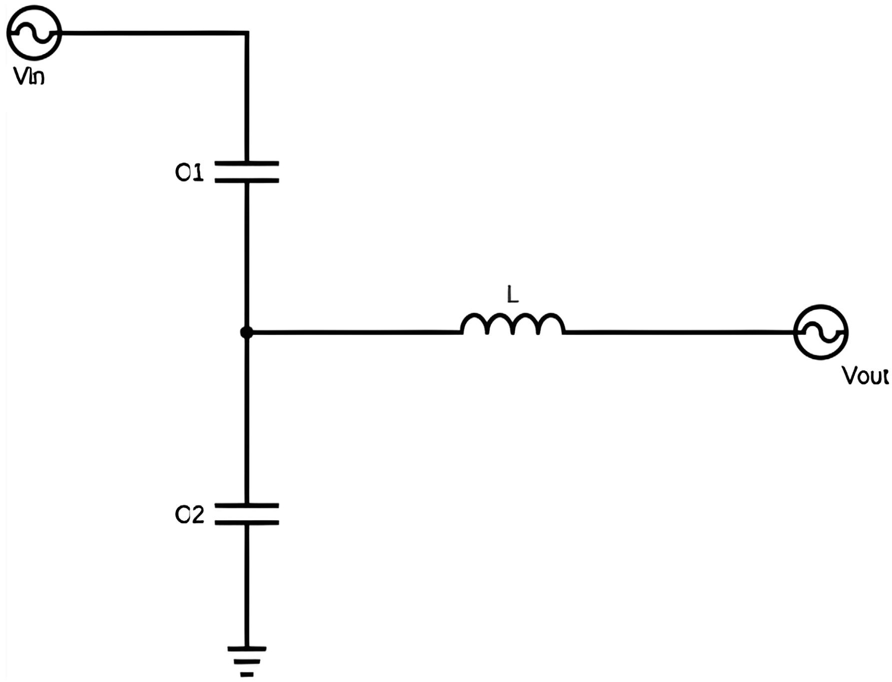

Figure 2. Simplified CCS Diagram [3].

represents Capacitor Bank 2.

The tap-voltage (VT) is calculated as follows in (1) below:

$$V_T = V_{in} \times \frac{C_1}{C_1 + C_2} \tag{1}$$

The output voltage is calculated as follows (2) below:

$$V_o = V_T - V_{L_1} \tag{2}$$

A typical connection of a CCS is shown in Figure 3 below:

Figure 3 above shows a typical connection of a CCS whereby:

Vs represents the Line Voltage, R_1/L_1, the line before the CCS tapping node, R_2/L_2, the line after the CCS tapping node, C_1 and C_2 are the coupling capacitors, R_{Load}, the tapping load measured through V_{ccs} across the tap, V_L, the measurement of the line response. The tapped voltage, V_T, is transmitted to a distribution network downstream via a step-down transformer. Research shows that a CCS is a cost-effective solution for supplying electricity to communities residing in close proximity to HV power lines. This is primarily due to the comparatively lower cost of a capacitor bank and a tuning reactor, as opposed to a traditional electromagnetic transformer [3] [11].

3.2. Simplified CCS with Power Tapping Node

A simplified equivalent circuit of a nominal-T model transmission line with a CCS system tapping power from an HV network is shown in Figure 4 below.

Figure 4 above shows an equivalent circuit whereby a CCS is used to tap power from an HV transmission line with $I_{CCS_{TAP}}$ being the input into a CCS

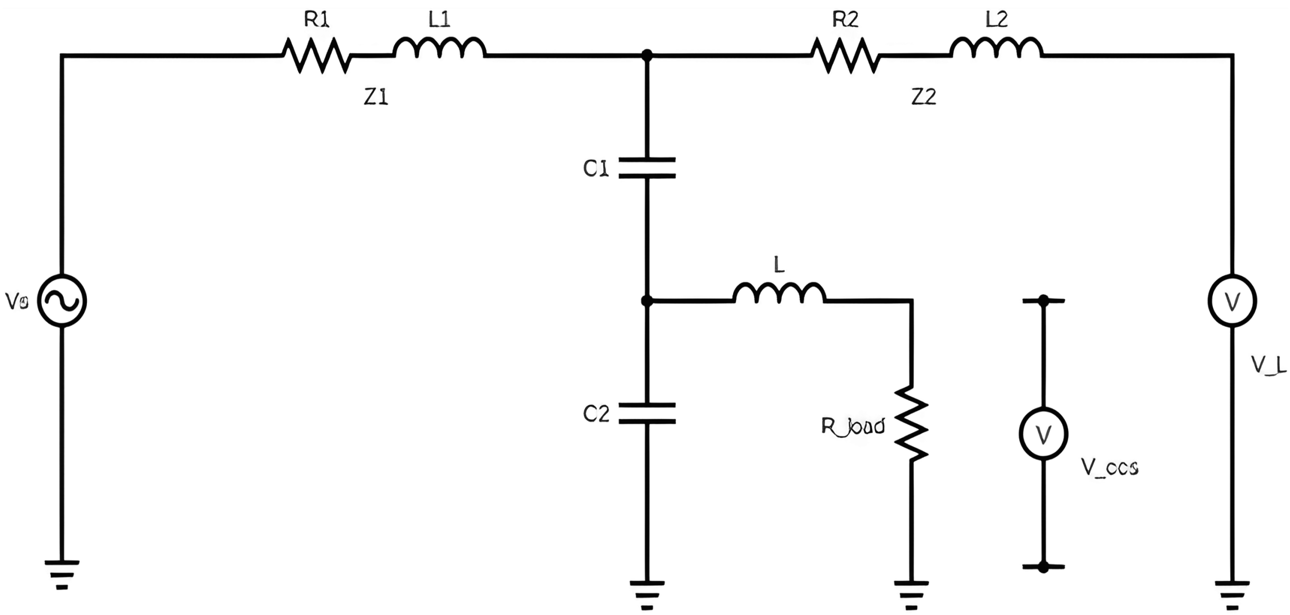

Figure 3. Typical CCS connection.

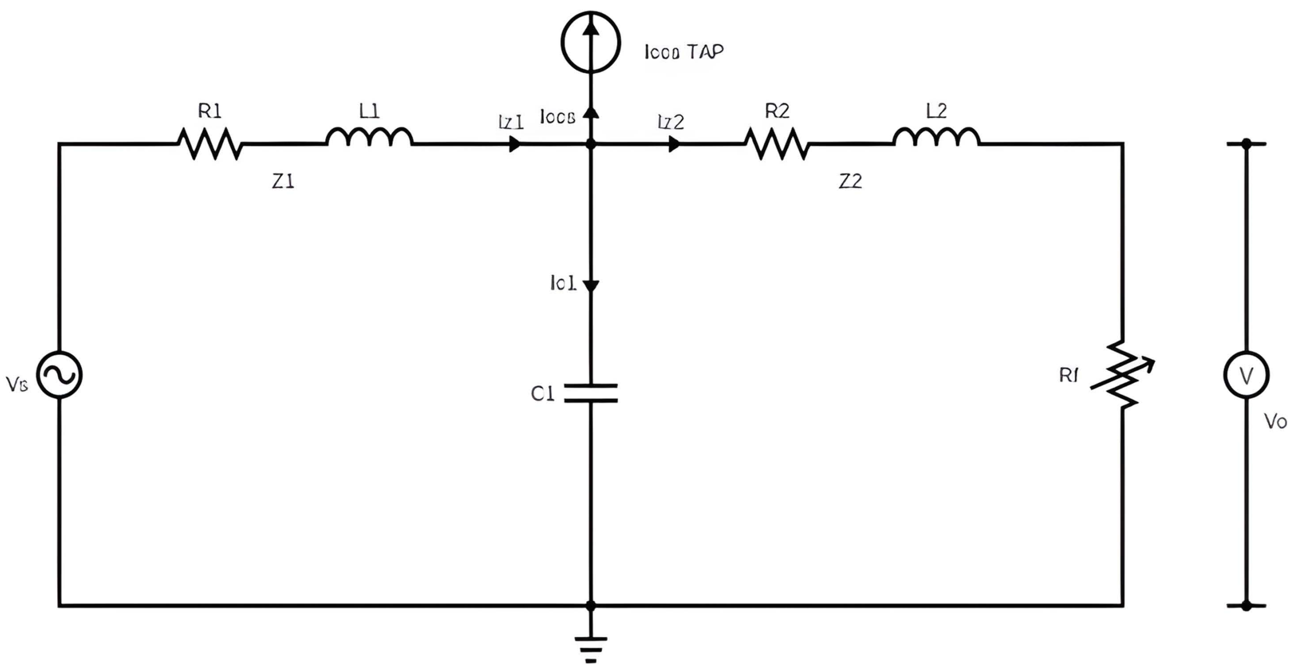

Figure 4. Transmission line CCS system equivalent circuit with power tapping.

circuit. Figure 4 was used to model the system response when power is tapped by the CCS from the transmission network and the resulting equations are summarized below by use of a loop method. The equivalent circuit was simplified into two loops.

4. Methodology

The simulation aimed to replicate the response of a typical transmission network when a loaded CCS is connected to it. In South Africa, the transmission network comprises of various high voltage levels. Typically, electricity is generated at 22 kV from a power generation plant and is then stepped up to either 220 kV, 275 kV, 400 kV, or 765 kV for transmission purposes. Subsequently, the voltage is stepped down to primarily 22 kV and/or 11 kV for residential distribution, although there are still 33 kV networks available for industrial use. In a residential network, there are commonly 22 kV/400V or 11 kV/400V transformers, from which the single-phase residential 230 V supply is connected.

The chosen CCS was simulated to tap electrical power from a 400 kV source and step it down to 400 V, which corresponds to the residential three-phase voltage. At the point of connection, the 230 V supply is derived from the 400 V using a "delta-star" or "delta-wye" configuration with a 400 V/230V transformer.

For the purpose of the model, the following approach was used:

- The transmission line voltage of 400 kV was selected.
- The required voltage of 400 V was selected as the tap volage.
- The voltage at the point of consumption was taken as 230 V.
- The coupling equivalent capacitor representing the capacitor banks or C1 was calculated.
- From the total capacitance, C1 and C2 were calculated from the charge formula,

$$Q = C \times HV,$$

where: Q is the charge, C is the capacitance and HV the voltage. For known HV of 400 kV and LV of 400 V at 50 Hz, the total capacitance was calculated using the formula $C = Q/(V \times F)$.

- The CCS Tap node was located 300 KM from the source and the downstream load was located 300 KM further downstream of the CCS tap-off node.
- The simulation was developed as per **Figure 5** below.

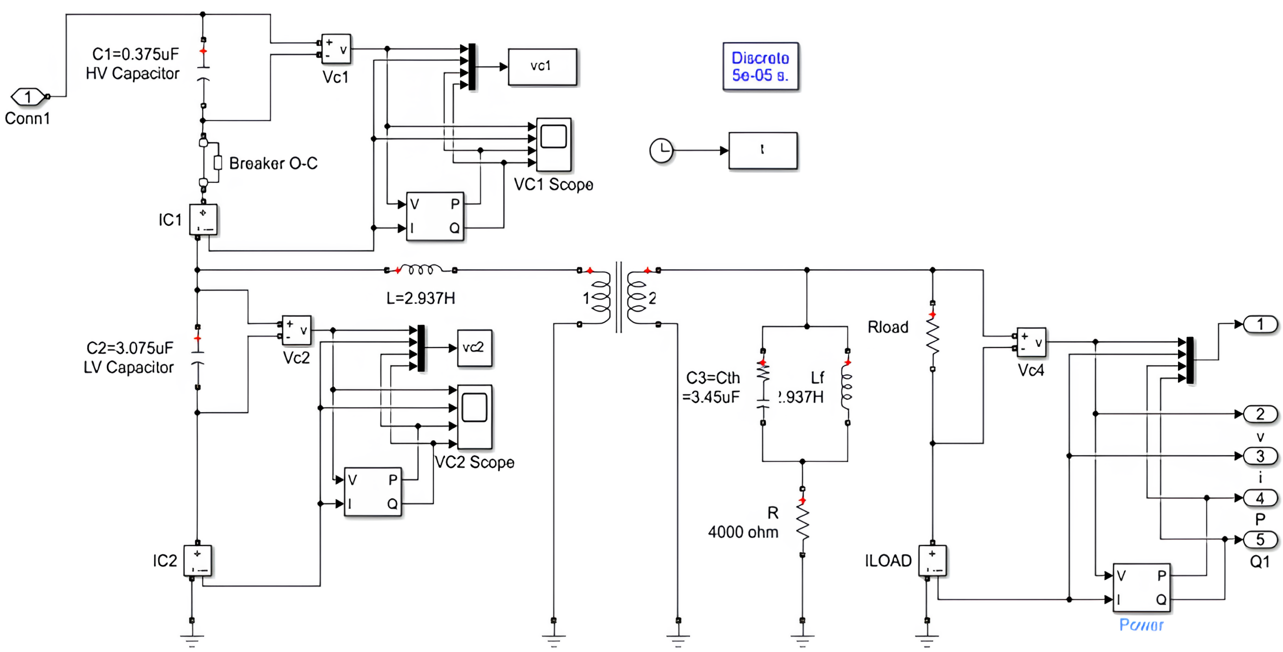

Figure 5. Single CCS model.

The circuit breakers were closed or open in the following sequence:

- Tx_1 CB_1—Closed at 0.016667 seconds;
- Tx CB_1—Closed at 0.16667 seconds;
- Tx CB_2—Closed at 0.18333 seconds;
- Tx CB_3—Closed at 0.2 seconds;
- CCS_{TAP} CB = Closed at 0.08333 seconds, opened at 0.3 seconds, and then closed again at 0.4 seconds.

Simulation Parameters

The simulation used the following parameters as shown on **Table 1** below.

The equations the power tapping of the CCS was implemented by applying a fixed load on the secondary side of the CCS, which had the ability to be connected or disconnected from the network.

To simulate any disturbances that may occur on the load, a fault was introduced to alter the power characteristics of the system. For the simulation, a 400 kVac input supply voltage was chosen, while the point of connection for the customer was set at 230 Vac. The objective of the simulation was to analyze the system's response when power is tapped from a CCS. To achieve this, a typical CCS was connected to a standard 400 kV transmission line network.

The previously mentioned line simulation model was used to observe the behavior of the line when a load is connected by a CCS circuit. The connected load was treated as a constant load that could either be connected or disconnected. The simulation was programmed to monitor the effects on the line's voltage and current levels.

5. Limitations of the Study

The power tapping of the CCS was implemented by applying a fixed load on the secondary side of the CCS, which had the ability to be connected or disconnected

Table 1. Model/simulation data.

Parameter	Values
Supply Voltage (Vs)	400 kVrms, 50 Hz
Peak Voltage (Simulink Setpoint) (Vp)	400 kV × $\sqrt{2}$ = 565.68 kV
Downstream Data	400 kVrms, 50 Hz, 50 MW Load
CCS C1	0.05 F
CCS C2	0.035 F
CCS Compensation Inductor (LMV)	2.5 μH
CCS Compensation Inductor (LLV)	2.5 μH
Step-Down Transformer	100 kVA, 400/230V
Point of Consumption Load	80 kW, 230 V, 50 Hz
Parameter	Values

from the network.

To simulate any disturbances that may occur on the load, a fault was introduced to alter the power characteristics of the system. For the simulation, a 400 kVac input supply voltage was chosen, while the point of connection for the customer was set at 230 Vac. The objective of the simulation was to analyze the system's response when power is tapped from a CCS. To achieve this, a typical CCS was connected to a standard 400 kV transmission line network.

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6. Results and Discussion

The objective of this article was to create a model and simulate the response of a transmission line when power is extracted by a typical CCS. The CCS was connected to the transmission system, and the changes in voltage and current characteristics of the transmission system were observed. **Figures 6-10** present the response of various system parameters, including the supply voltage, downstream line voltage, CCS tap voltage before the step-down transformer, and CCS point of consumption voltage, when the CCS was connected into the transmission line as the model on **Figure 5**.

Figures 12-15 present the response of various system parameters, including the supply, line, CCS before the transformer, and CCS after the transformer, when the supply voltage was set at 400 kVac and the CCS Load was set at 80 kW, as simulated in **Figure 11** below with an applied line-line-earth fault that was deliberately introduced on the CCS after the transformer, as shown in **Figure 11**.

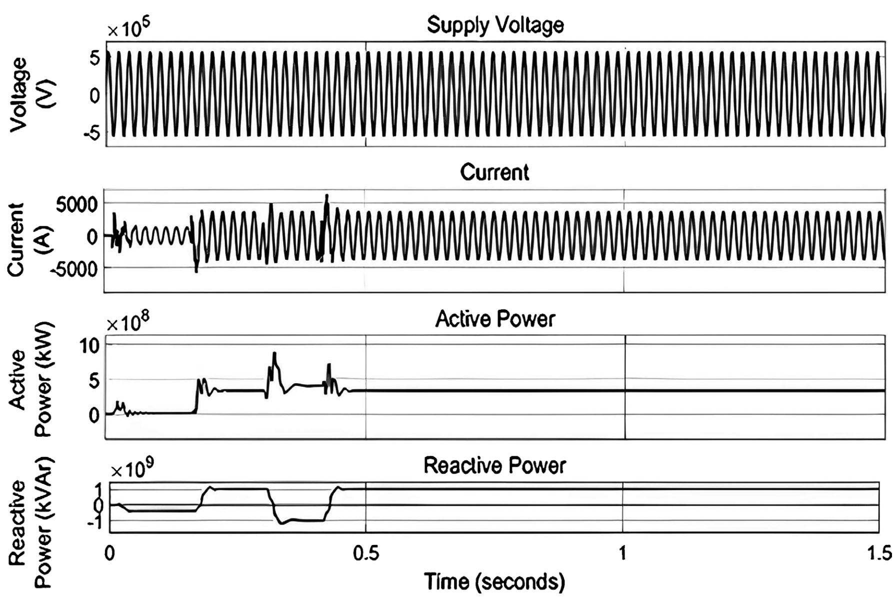

Figure 6. Supply parameters.

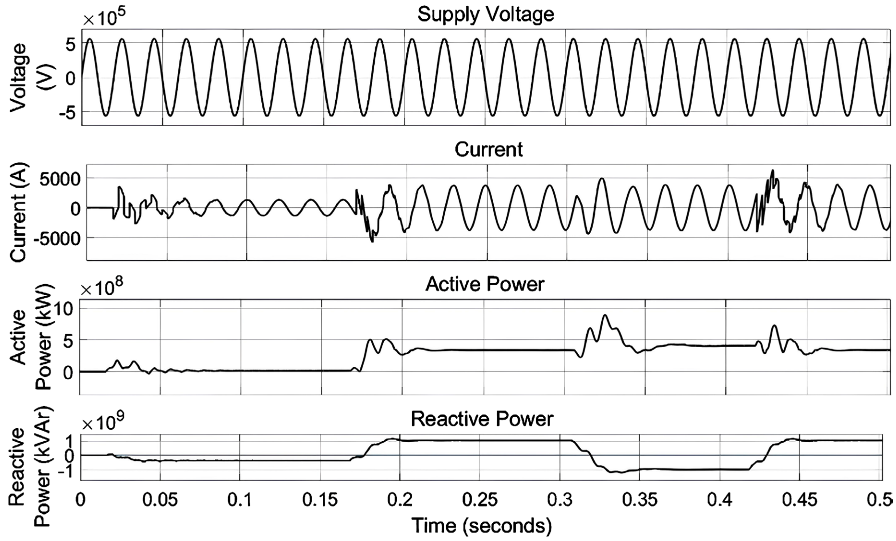

Figure 7. Supply parameters-reduced time span.

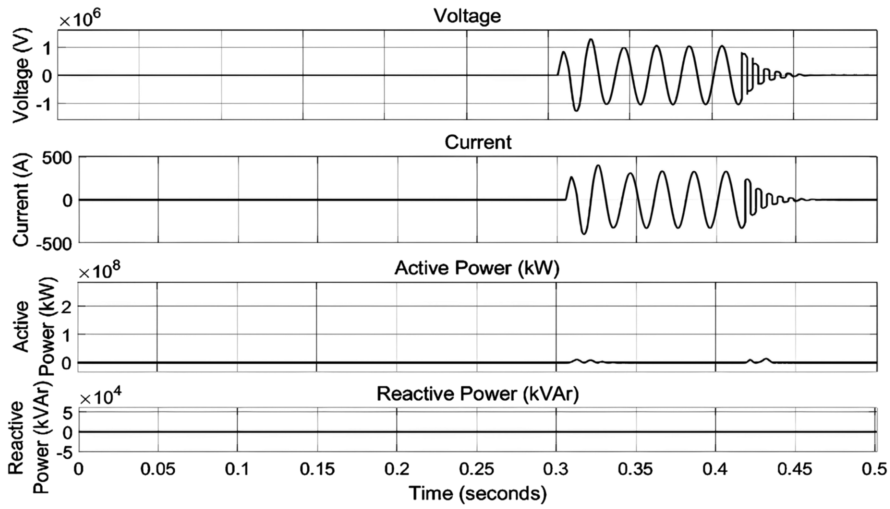

Figure 8. Downstream parameters-reduced time span.

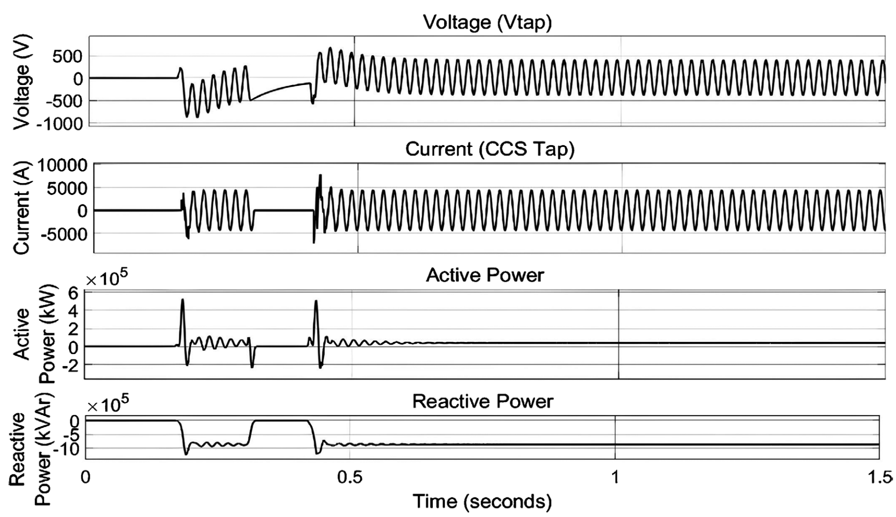

Figure 9. CCS tap parameters.

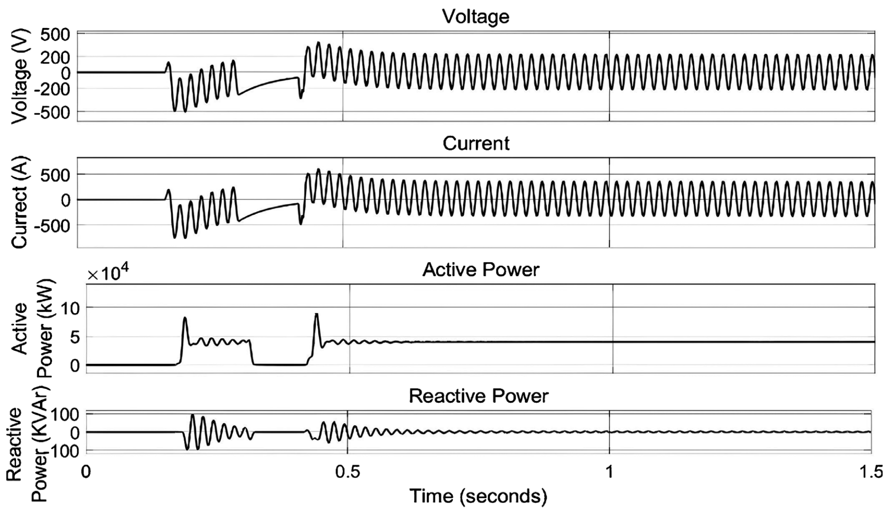

Figure 10. Point of consumption parameters.

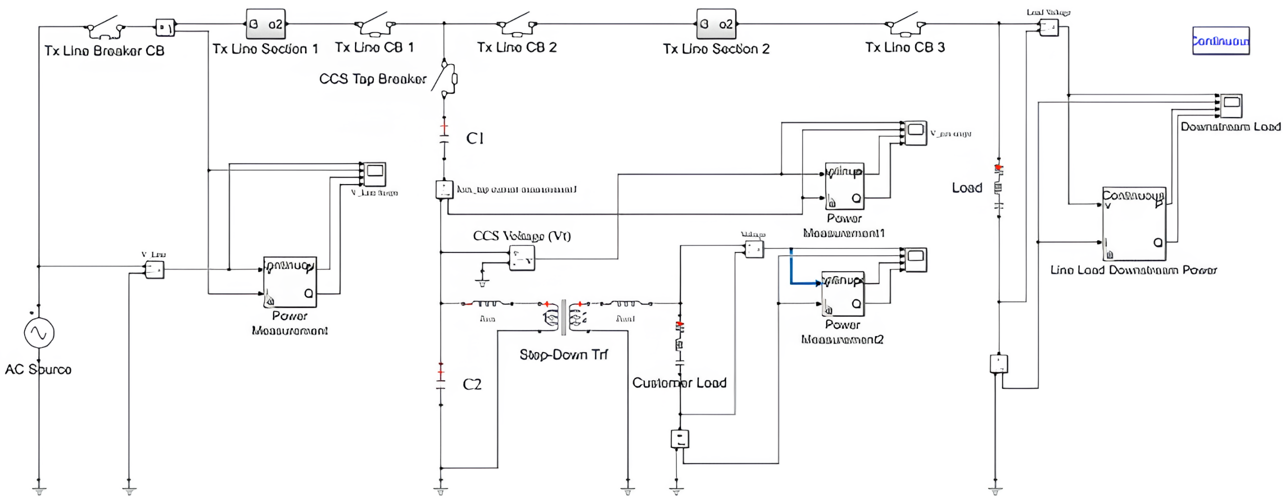

Figure 11. Model with fault applied.

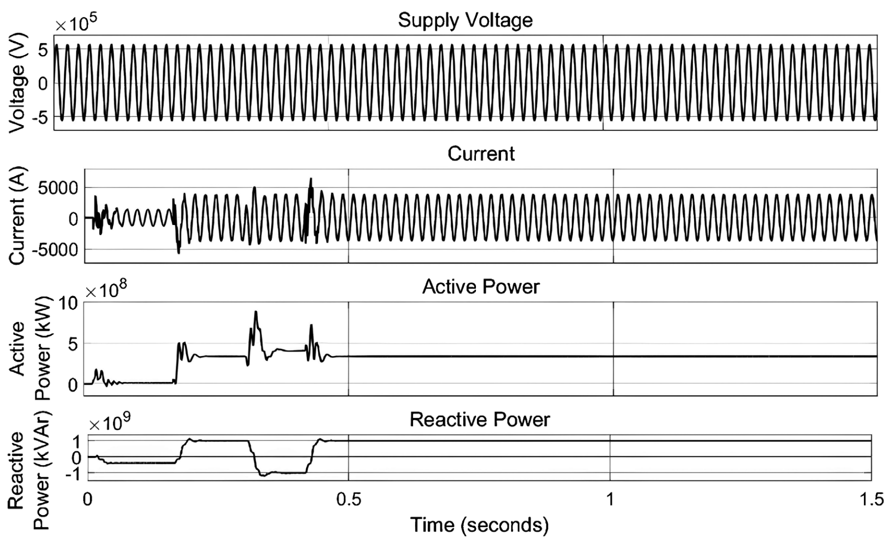

Figure 12. Supply parameters under fault conditions.

The results of this validation are presented in **Figures 12-15**.

The results show that there were negligible disturbances to the network during the switching of different breakers. This suggests that the transmission line treats the CCS as a singular load. The behavior of the CCS affects the system in a similar manner to a conventional load would.

The findings further indicate that when a fault occurs on the CCS, the entire system is affected. An essential parameter monitored was the supply voltage, which remained unaffected by downstream activities. However, the results depicted in **Figure 13** and **Figure 14** demonstrate interference on the CCS parameters during fault conditions. While there is some interference observed on the tap voltage, the impact on the supply voltage remains minimal. Therefore, it is crucial to conduct further investigation and analysis on the influence of CCS

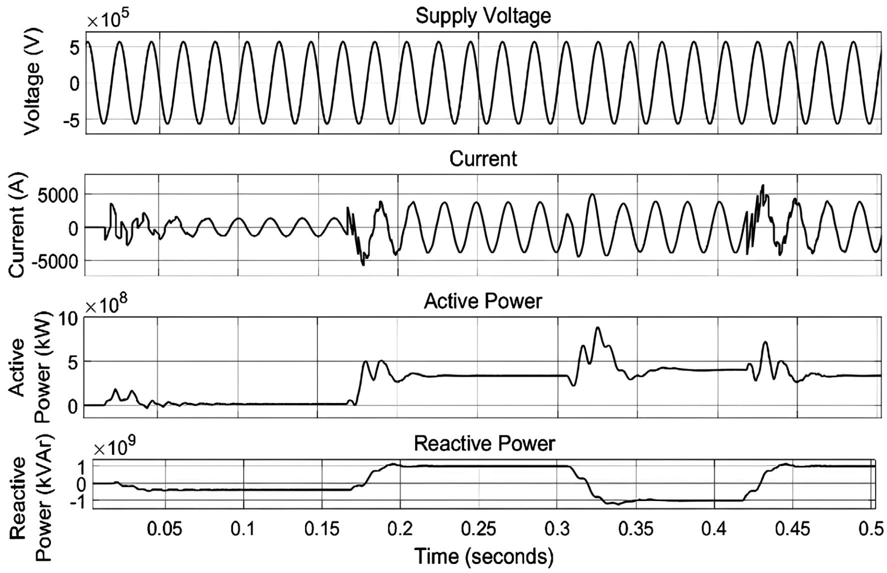

Figure 13. Supply parameters under CCS node fault.

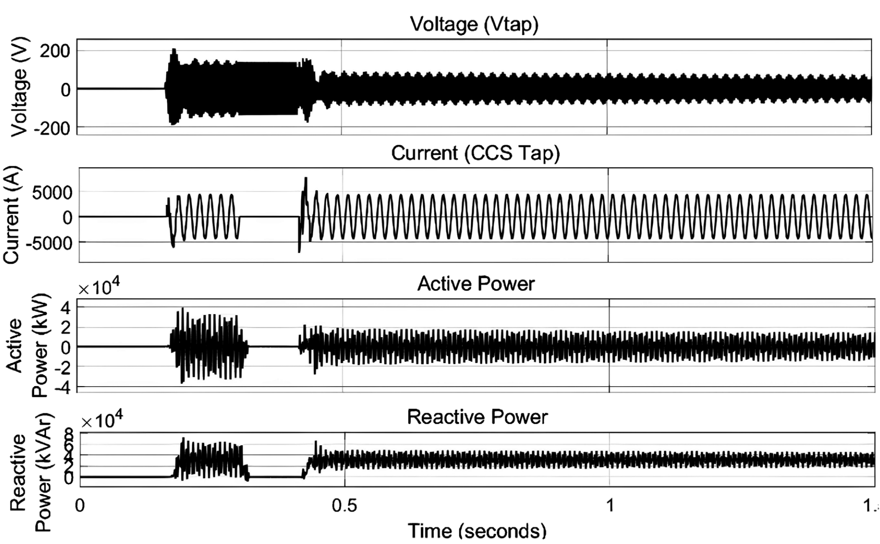

Figure 14. CCS tap node with fault.

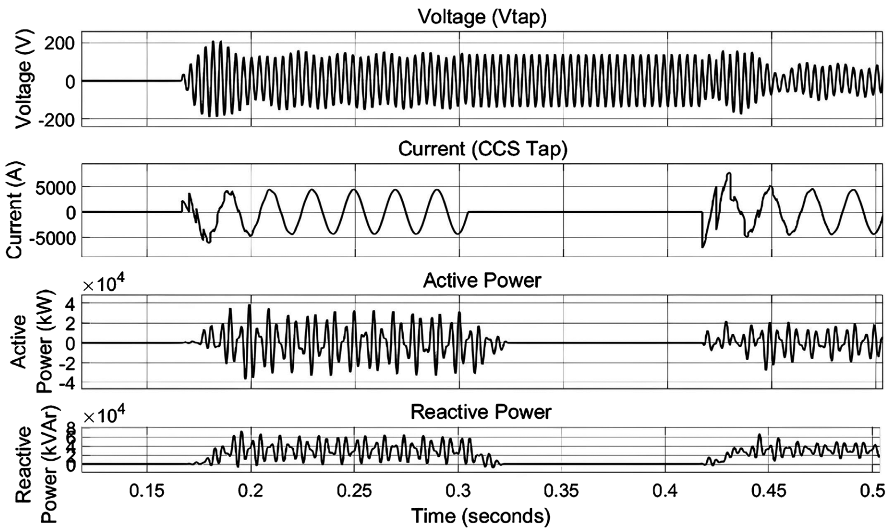

Figure 15. CCS tap with fault—expanded span.

tapping within a network under normal and fault conditions. This will ensure that the objectives of the CCS tapping process are successfully achieved.

7. Practical Implications and Applications of the Research

This research is part of an ongoing research that aims at modeling and analyzing the transmission network response when a CCS-CNT is connected to it. The application of the CNT is primarily to allow bi-directional power flow control to allow micro-grids to be connected to the main transmission lines without the requirement of extensive grid-tie inverters. Secondary to the power control application, the CNT can also be used for the system ferroresonance suppression as a ferroresonance suppression circuit. The CCS studied on this paper can be adopted for use as a rural electrification technology for sparsely populated areas.

8. Conclusions

The simulation results demonstrated that, in normal operating conditions, minimal interference occurs when a CCS is connected to the system, without considering the ratings of all the connected CCS elements. However, to comprehensively observe and analyze the system response to the CCS, it is necessary to develop and integrate a complete CCS model into the circuit.

The introduction of a fault condition further emphasized the importance of analyzing the behavior of a complete CCS system, as abnormal conditions impact not only the CCS but also the main supply voltage. It should be noted that the applied fault was specifically used to assess the behavior of the line and CCS parameters. These findings serve as a foundation for analyzing the system response when a CCS-CNT system is connected to the network.

9. Recommendations

1) To develop a complete CCS model including the ferroresonance suppres-

sion circuit (FRSC) and the distribution transformer of the CCS and study the system network response when power is tapped off.

2) Propose a complete CCS model without FRSC but with a distribution transformer replaced with a controllable network transformer (CNT) together with its control strategy to help in suppressing the inherent ferroresonance of CCS.

3) Since a CCS taps power from the high voltage (HV) lines to feed rural dwellings, the vast area of land around these rural areas can be used to harness energy from the sun or wind which then can be fed back into the grid. Hence, the proposed CCS-CNT will be used for power tapping and power injection on the transmission line through classical control of CNT.

Acknowledgements

The authors express heartfelt gratitude to the Tshwane University of Technology for the ongoing unwavering support during this research work.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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