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Mathematical Modeling of Multiple Capacitor Coupled Substations (CCS) Impact on Transmission Lines and Approaches for Ferroresonance Suppression

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Abstract

Rural electrification remains a critical challenge in achieving equitable access to electricity, a cornerstone for poverty alleviation, economic growth, and improved living standards. Capacitor Coupled Substations (CCS) offer a promising solution for delivering cost-effective electricity to these underserved areas. However, the integration of multiple CCS units along a transmission network introduces complex interactions that can significantly impact voltage, current, and power flow. This study presents a detailed mathematical model to analyze the effects of varying distances and configurations of multiple CCS units on a transmission network, with a focus on voltage stability, power quality, and reactive power fluctuations. Furthermore, the research addresses the phenomenon of ferroresonance, a critical issue in networks with multiple CCS units, by developing and validating suppression strategies to ensure stable operation. Through simulation and practical testing, the study provides insights into optimizing CCS deployment, ultimately contributing to more reliable and efficient rural electrification solutions.

Keywords

Capacitor Coupled Substation, Ferroresonance, Power System, Modelling, Algorithm Presentation, Rural Electrification

1. Introduction

With the need for increased access to electricity, rural areas are still left behind [1]. Electricity is at the center of poverty alleviation, economic growth, and improved living standards [2] [3]. Capacitor Coupled Substation (CCS) are one of the technologies that can be used to deliver cost-effective electricity to these rural areas [4]. To deliver electricity to different locations located at different areas along the same transmission line requires the understanding of the impact multiple CCS has on a transmission line. The introduction of multiple CCS units along a transmission line presents both opportunities and challenges. While CCSs can enhance power quality and reliability, their presence can also lead to complex interactions within the network, particularly when multiple units are placed at varying distances from each other [5] [6]. These interactions can significantly affect key network parameters such as voltage, current, active power, and reactive power.

Understanding and mitigating these effects requires a robust mathematical framework. The proposed study develops a detailed model to analyze the impact of multiple CCS units on a transmission network, considering the proximity between CCSs and their operational states. The objective is to determine how different configurations and distances between CCSs influence the network's stability and power quality. The distance selected was 300km based on the perceived distances that may exist between two rural settings.

This research also addresses the phenomenon of ferroresonance, a nonlinear resonance that can occur in electrical systems due to the interaction between inductance and capacitance [7]. In a network with multiple CCS units, ferroresonance poses a significant risk, potentially leading to overvoltages and instability [8] [9]. Therefore, an integral part of this study involves developing and validating strategies for ferroresonance suppression to ensure the stable operation of transmission networks equipped with multiple CCSs.

A detailed mathematical algorithm for modeling and analyzing the impact of multiple CCS units on a transmission network, including the steps for simulation, validation, and interpretation of results is presented. The study aims to provide a comprehensive understanding of the behavior of networks with multiple CCSs and to identify optimal configurations that minimize disturbances and enhance overall network performance.

2. Mathematical Algorithm for Multiple CCS Model Representation

The objective of this article is to develop a mathematical representation that can be used to model and analyze the impact of multiple Capacitor Coupled Substations (CCS) on a transmission network, particularly focusing on the proximity between CCSs and their effects when connected or disconnected. The aim is to assess how different configurations and distances between CCSs affect network parameters like voltage, current, active power, and reactive power. The representation is designed such that any distance between more than one CCS can be modelled. The strategy employed is defined in the following sections.

2.1. Define the CCS Model

A CCS model to be considered must be defined. A basic MATLAB/Simulink CCS model is presented in **Figure 1** and **Figure 2** presents a basic simplified CCS.

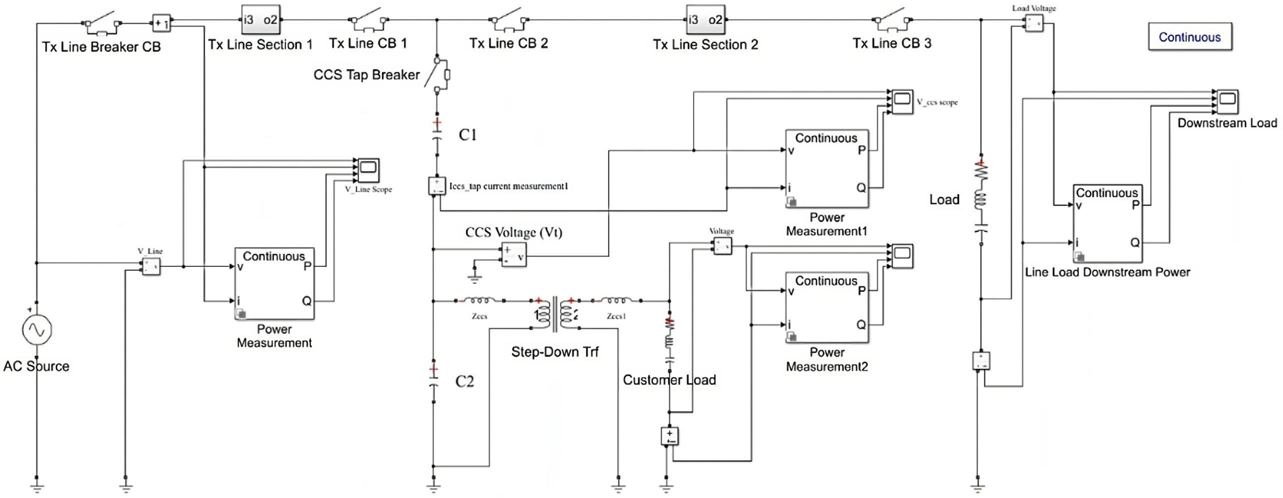

Figure 1. Single CCS model.

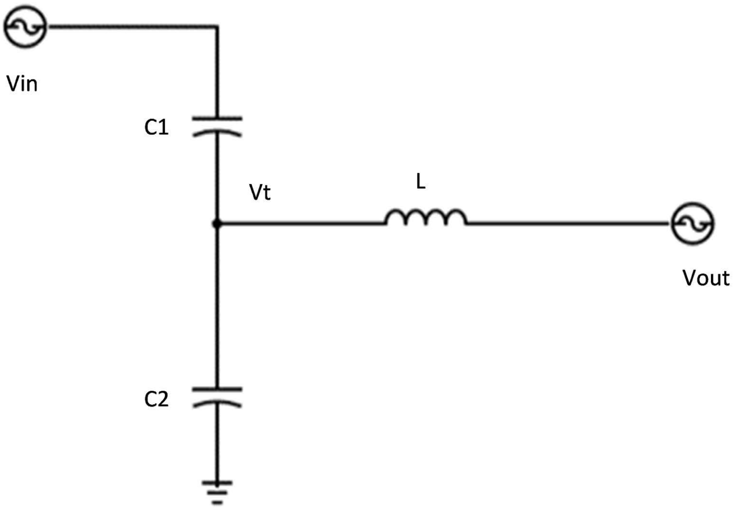

Figure 2. Simplified basic CCS.

In a multiple CCS, each CCS can be represented using a simplified equivalent circuit model as presented in **Figure 2** with:

- C_1 and C_2: Capacitor banks.
- L: Inductor representing the inductive effects.
- V_T: Tap voltage at the node between C_1 and C_2.
- V_{out}: Output voltage after subtracting the voltage drop across the inductor L. designations.

Given:

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

$$V_{out} = V_T - V_L$$

where:

- V_{in} is the input voltage from the HV transmission line.
- V_L is the voltage drop across the inductor.

2.2. Model the Transmission Line with Multiple CCS

A model representation of multiple CCS is given in **Figure 3**, which is the combination of a number of CCS. This basic model is used as the basis for modelling. However, any number of CCS can be incorporated into the system.

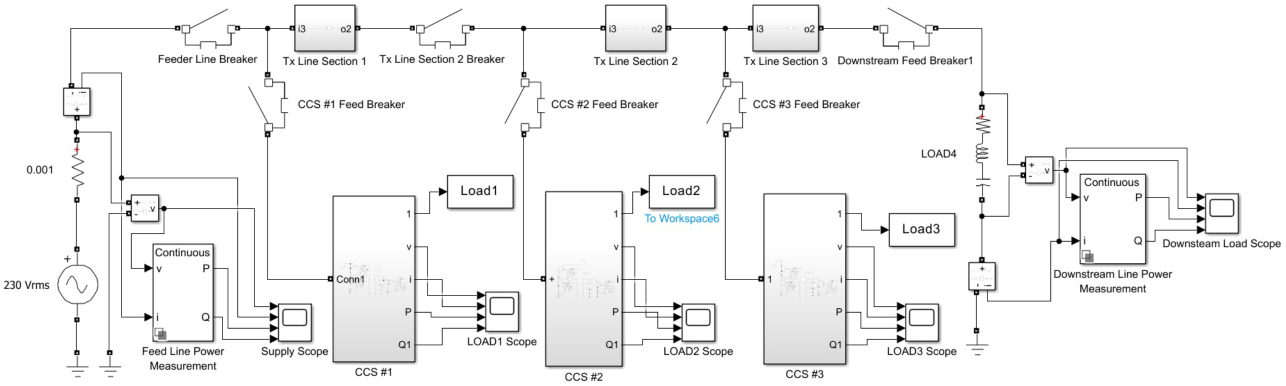

Figure 3. Multiple CCS representation.

Assume a transmission line of length L_t with N CCSs placed at distances, $d_1, d_2, \cdots, d_N$ from the source.

For each CCS:

- Define the impedance of the transmission line between the source and CCS i as:

$$Z_{line,i} = R_{line,i} + X_{line,i}$$

where:

$R_{line,i}$ is the resistance of the line segment up to CCS i.

$X_{line,i}$ is the reactance of the line segment up to CCS i.

- The voltage at the location of CCS i is:

$$V_i = V_{in} - I_i \times Z_{line,i}$$

The current drawn by the CCS i is:

$$I_i = \frac{V_T}{Z_{CCS,i}}$$

where:

$Z_{CCS,i} = R_{CCS,i} + jX_{CCS,i}$ is the impedance of the CCS i including its internal elements.

- Update the system impedance for downstream CCSs after connecting CCS i.
- Iterate for all CCSs in the system to obtain the voltage, current and power at each point in the network.

2.3. Analyze the Impact on Network Parameters

- Reactive Power Fluctuations:
    - Each CCS introduces a reactive power component due to the capacitive nature of C_1 and C_2.
    - The total reactive power Q at any point is the sum of contributions from all connected CCSs and is given by:

$$Q_{total} = \sum_{i-1}^{N} Q_{CCS,i}$$

- Voltage and Current Profiles
    - Analyze the voltage V_{line} profile along the transmission line, where:

$$V_{line} = f\left(d_i, Z_{line,i}, Z_{CCS,i}, V_{in}\right)$$

    - Calculate the current $I_{line,i}$ flowing through each section of line considering the effect of connected CCSs, where:

$$I_{line,i} = \frac{V_i}{Z_{line,i}}$$

- Power Flow Analysis
    - Calculate the active power P_i and reactive power Q_i power flow in the system before and after connecting each CCS, using:

$$P_i = V_i \times I_i \times \cos\left(\theta_i\right)$$

$$Q_i = V_i \times I_i \times \sin\left(\theta_i\right)$$

where θ_i is the phase angle between voltage and current.

2.4. Simulation and Validation

- Use MATLAB/Simulink to simulate the system with varying distances between CCSs.
- Validate the results through practical testing using prototypes and digital tests with oscilloscopes.
- Compare the results obtained from the simulation, physical prototypes, and digital tests to ensure consistency.

2.4.1. Simulation Steps

The three following simple steps can be used during simulation, vis.:

- **Initialize the system:** Set initial conditions with all CCS breakers open.
- **Sequentially close CCS breakers:** Observe the impact on system voltage, current, and power as each CCS is connected.
- **Vary the distances:** Repeat the simulations for different distances (e.g., 300 km) between CCSs.

MATLAB can be used to simulate a number of parameters that may be required. Example of a MATLAB code used to simulate the voltage drop across the transmission line with three CCS units placed 300 km apart, each with a load of 80 kW at 11 kV is given by:

```
% Parameters
V_in = 132e3; % Transmission line voltage in Volts (132 kV)
V_tap = 11e3; % Tapped voltage at CCS in Volts (11 kV)
P_load = 80e3; % Load at each CCS in Watts (80 kW)
distance = 300e3; % Distance between CCS units in meters (300
km)

% Transmission line parameters (assumed)
R_line_per_km = 0.1; % Resistance per km of the transmission
line in Ohms
X_line_per_km = 0.2; % Reactance per km of the transmission
line in Ohms

% CCS impedance parameters (assumed)
R_CCS = 0.01; % Resistance of CCS in Ohms
X_CCS = 0.05; % Reactance of CCS in Ohms

% Calculate impedances
Z_line = @(d) (R_line_per_km + 1i*X_line_per_km) * (d/1e3); %
Impedance of line segment in Ohms
Z_CCS = R_CCS + 1i*X_CCS; % Impedance of CCS in Ohms

% Initialize voltage at the source
V = V_in;

% Initialize results
voltage_drop = zeros(1, 3); % Voltage drop for each CCS
voltage_at_CCS = zeros(1, 3); % Voltage at each CCS

for i = 1:3
    % Calculate current drawn by each CCS
    I_CCS = P_load / (V_tap * sqrt(3)); % Assuming power fac-
tor = 1

    % Calculate voltage at the location of each CCS
    V_CCS = V - I_CCS * Z_line(distance * i); % Voltage after
impedance drop

    % Calculate voltage drop across CCS
    voltage_drop(i) = abs(V - V_CCS);

    % Update the voltage at CCS
    voltage_at_CCS(i) = abs(V_CCS);

    % Update voltage for the next iteration
    V = V_CCS - I_CCS * Z_CCS; % Voltage after CCS drop
end

% Display results
disp('Voltage drops at each CCS location (in volts):');
disp(voltage_drop);

disp('Voltages at each CCS location (in volts):');
```

This code can be run in MATLAB to simulate the voltage drop across the transmission line with three CCS units placed 300 km apart, each with a load of 80 kW at 11 kV. Adjust the parameters as needed based on your specific study requirements. The selection of the parameters was based on a typical CCS load that a small village may require. The load was extrapolated from one of the distribution transformers located in a village of Emakholweni, in Umbumbulu, the Republic of South Africa, where the distribution transformer is a 100kVA. Therefore, a load of 80 kW was selected for the study.

2.4.2. Prototype Model Data

A prototype model developed used parameters selected based on the available equipment. Table 1 presents the selected prototype parameters used, where all the three CCS were identical.

Table 1. CCS prototypes parameters.

Parameter	Value
C_1	0.375 μF
C_2	3.075 μF
L	2.937 H
Step-down Transformer	1000 VA, 50 Hz, 230/110 V
Load	Fixed resistive load of 200 Ω

The downstream parameters selected are presented in Table 2.

Table 2. CCS prototypes downstream parameters.

Parameter	Value
Nominal Voltage	230 V_{rms}
Nominal Frequency	50 Hz
Active Power	100 kW
Inductive Reactive Power	100 (+VAR)
Capacitive Reactive Power	100 (−VAR)

Parameters monitored during the testing are presented in Table 3.

Table 3. CCS prototypes monitored paramters.

Parameter	Details
Supply Voltage	Line Voltage
Downstream Parameters	Line Voltage and Current, Load Voltage and Current, Load Active Power and Load Reactive
CCS Parameters	Voltage and Current, Load Active Power and Load Reactive Power.

The experimental data used, selected purely on the limited available resources, is presented in Table 4.

Table 4. CCS prototypes representation parameters.

Values	CCS #1	CCS #2	CCS #3
Load Resistor	2.2 kΩ	2 kΩ	15 Ω
MV Inductor	17.2 Ω	1.3 kΩ	15.2 Ω
LV Inductor	0.4 Ω	2.6 kΩ	15 Ω
Step-down Transformer	525/230	230/110	525/230

Continued

Line Resistance Measuring Points	Resistance
Source to Line 1	279 Ω
Line 1 to Line 2	326 Ω
Load	2.6 kΩ

The result of the simulation is presented in Table 5 where the measurements were taken from the points as demonstrated in Figure 4.

Table 5. CCS prototypes final results.

Measured Point	CCS #1 (V)	CCS #2 (V)	CCS #3 (V)
A	230	230	230
B	30	31.8	28.9
C	30	31.8	10.4
C-C1	0.18	3.9	18.5
D	12	14.9	4.3
D-D1	No Reading	1.9	4.2
E	10	14.9	0.59

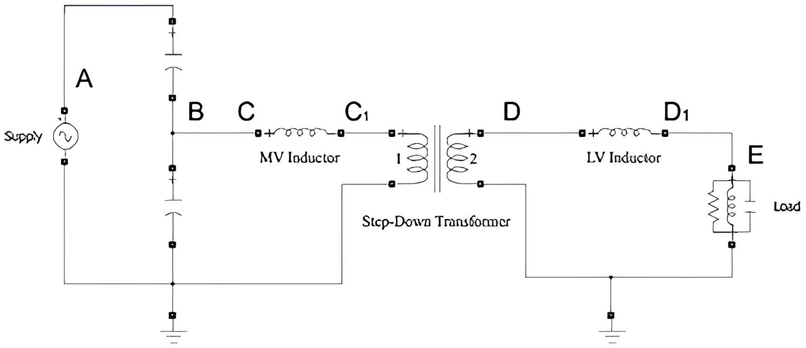

Figure 4. CCS testing points.

2.4.3. Verification of the Approach Using Different Parameters

A verification approach was used using different parameters of the CCS where the supply voltage was selected as 230 kVrms and the downstream load was 100 kW, with the three identical CCS. The focus was on the supply voltage interference when the CCSs were connected to it. The results are presented in Figures 5-9.

2.5. Interpreting the Results

- Analysing the impact of CCS proximity on network stability and power quality.
- Identify critical distances or configurations where reactive power fluctuations or voltage disturbances are minimized.

From both the modelled results and the tested results, it shows that when the CCSs are switched into the system, there is no notable interference on the supply voltage, which could imply system instability is a real life setting if there was any observed interference and drastic changes in the tested voltage at different points.

The parameters selected for the model, were based on a typical transmission network voltage of 230 kVrms, while the prototypes were built for the laboratory available 230 Vrms system. The distances for the prototypes were represented by the resistances. These values were arbitrarily selected to observe the system behaviour in the event of distance changes. The observed reactive power fluctuations from **Figures 4-8**, can be attributed to switching transients as they are present only after a CCS is switched either ON or OFF. The test on the prototypes did not consider any power flow, its main focus was the behaviour of the supply voltage as the results in **Table 5** show that the supply voltage magnitude was not affected by the switching ON of the CCSs.

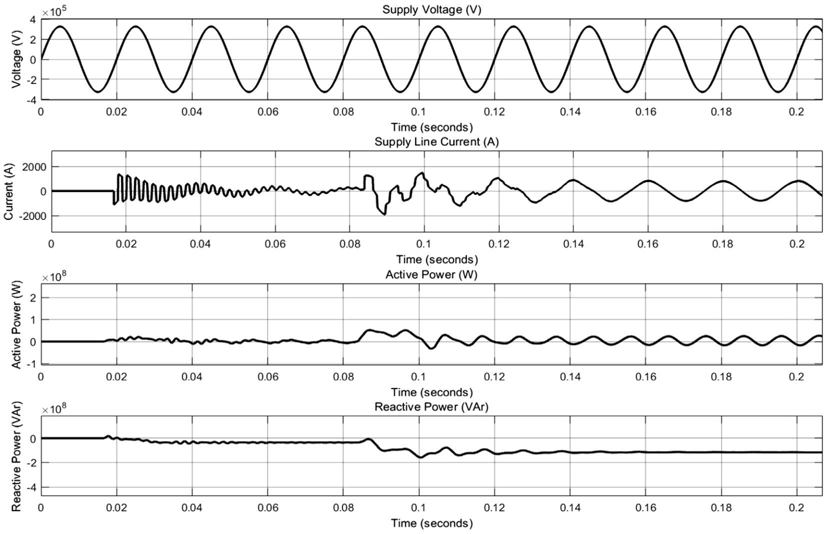

Figure 5. Supply parameters.

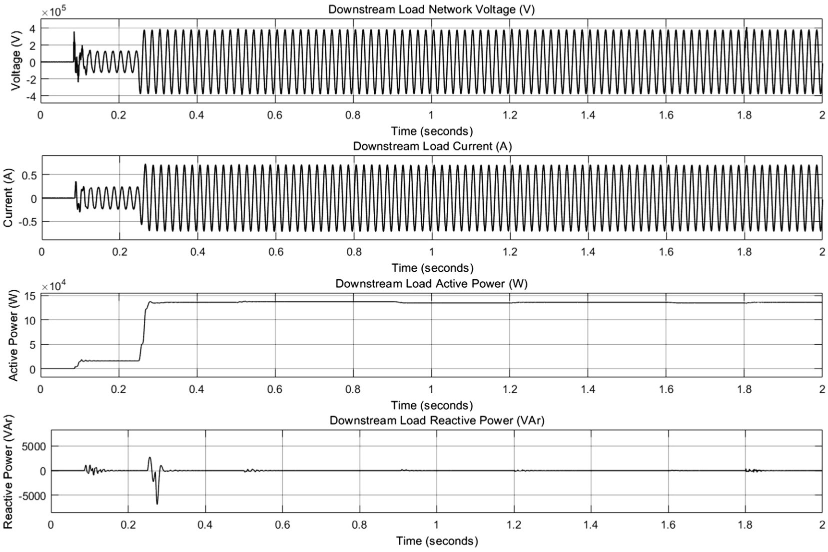

Figure 6. Downstream paramters.

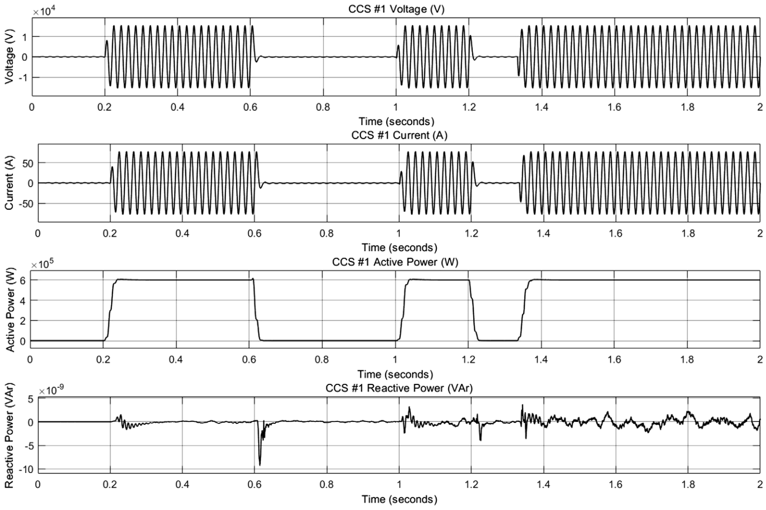

Figure 7. CCS 1 parameters.

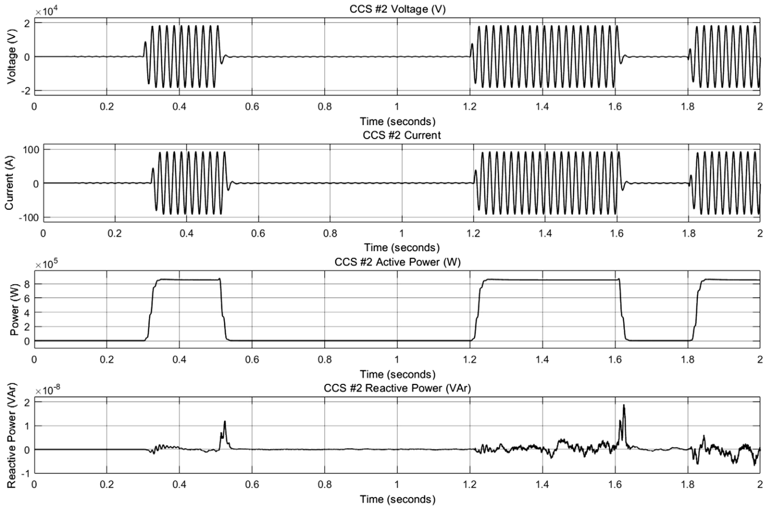

Figure 8. CCS 2 parameters.

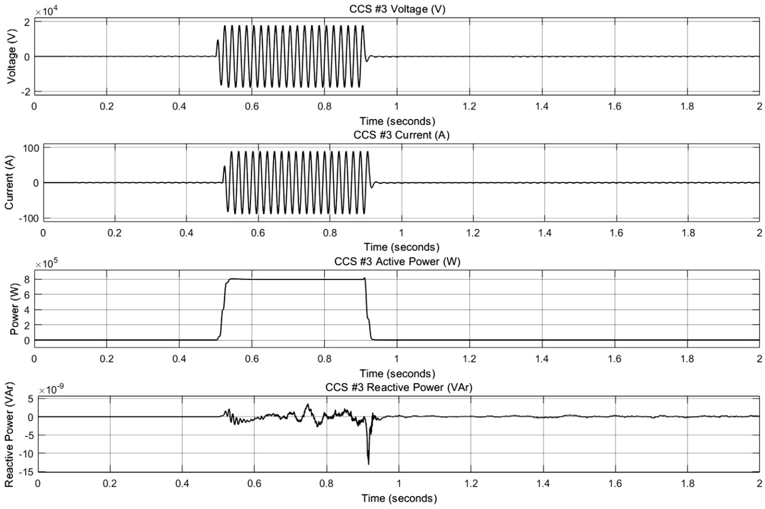

Figure 9. CCS 3 parameters.

3. Ferroresonance Suppression on Multiple CCSs Systems

Ferroresonance is a nonlinear resonance phenomenon in electrical systems, often occurring when inductance interacts with capacitance in an unintended manner [10] [11]. In the context of the Capacitor Coupled Substations (CCS), particularly when multiple CCS units are placed at different proximities on a transmission network, suppression of ferroresonance is critical to maintaining system stability and avoiding overvoltages [12] [13] [14]. Ferroresonance can be suppressed by a number of approaches, one being the conventional technique of Resistor-Capacitor-Inductor (RLC) [15].

To mathematically represent ferroresonance suppression in a network with multiple CCSs, consider the following elements:

- Capacitive Reactance (X_C) of the CCSs, related to the capacitance C and given by:

$$X_C = \frac{1}{\omega C}$$

where ω is the angular frequency of the system.

- Inductive Reactance (X_L) of the system inductance (L):

$$X_L = \omega L$$

- System Impedance (Z_s) that combines inductance and capacitance:

$$Z_s = \sqrt{X_L^2 + \left(\frac{1}{nX_C}\right)^2}$$

where n is the number of CCS units.

- Resonance Frequency ω_r where resonance occurs:

$$\omega_r = \frac{1}{\sqrt{L \times C_{eq}}}$$

where C_{eq} is the equivalent capacitance considering all CCS units:

$$C_{eq} = \frac{C}{n}$$

- Damping Factor (ζ) to suppress resonance:

$$\zeta = \frac{R}{2\sqrt{L/C_{eq}}}$$

where R is the system resistance.

The ferroresonance suppression condition requires that the damping factor ζ is sufficiently high to prevent oscillation. Therefore, to ensure suppression:

$$\zeta \geq 1$$

This translates into a suppression criterion:

$$R \geq 2\sqrt{\frac{L}{C_{eq}}}$$

This equation can be adapted for the case of multiple CCSs at different proximities by considering the equivalent parameters for the entire network.

4. Conclusion

This study highlights the crucial role of Capacitor Coupled Substations (CCS) in expanding access to electricity in rural areas, which is essential for poverty alleviation and economic growth. The research emphasizes the importance of understanding the complex interactions that arise when multiple CCS units are integrated into a single transmission network. These interactions, which affect voltage, current, and power flow, present both opportunities for enhancing power quality and challenges, particularly in mitigating issues such as ferroresonance. The development of a robust mathematical model and simulation framework provides valuable insights into optimizing the configuration and placement of CCS units. The algorithm provides a structured approach to model and analyze the impact of multiple CCSs on a transmission network. This ensures network stability, minimizes disturbances, and enhances overall performance. The proposed ferroresonance suppression strategies further contribute to maintaining system stability, ensuring the reliable operation of transmission networks equipped with multiple CCSs. Ultimately, this research offers a comprehensive understanding and practical solutions for deploying CCS technology in rural electrification projects, thereby contributing to broader efforts in bridging the electricity access gap in underserved regions.

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Conflicts of Interest

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

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