

Mathematical Modeling and Control Algorithm Development for Bidirectional Power Flow in CCS-CNT System

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Abstract

As the demand for more efficient and adaptable power distribution systems intensifies, especially in rural areas, innovative solutions like the Capacitor-Coupled Substation with a Controllable Network Transformer (CCS-CNT) are becoming increasingly critical. Traditional power distribution networks, often limited by unidirectional flow capabilities and inflexibility, struggle to meet the complex demands of modern energy systems. The CCS-CNT system offers a transformative approach by enabling bidirectional power flow between high-voltage transmission lines and local distribution networks, a feature that is essential for integrating renewable energy sources and ensuring reliable electrification in underserved regions. This paper presents a detailed mathematical representation of power flow within the CCS-CNT system, emphasizing the control of both active and reactive power through the adjustment of voltage levels and phase angles. A control algorithm is developed to dynamically manage power flow, ensuring optimal performance by minimizing losses and maintaining voltage stability across the network. The proposed CCS-CNT system demonstrates significant potential in enhancing the efficiency and reliability of power distribution, making it particularly suited for rural electrification and other applications where traditional methods fall short. The findings underscore the system's capability to adapt to varying operational conditions, offering a robust solution for modern power distribution challenges.

Keywords

Capacitor Couple Substation, Ferroresonance, Power Flow Control, Controllable Network Controller, Capacitor-Coupled Substation Incorporating Controllable Network Transformer (CCS-CNT) System, System Modeling

1. Introduction

As the demand for efficient and flexible power distribution systems grows, especially in rural areas, the need for advanced solutions like the Capacitor-Coupled Substation with a Controllable Network Transformer (CCS-CNT) becomes apparent [1] [2]. Traditional power distribution networks often struggle to meet the complex demands of modern energy systems, especially with the integration of renewable energy sources and the need for reliable electrification in underserved regions [3] [4]. In this context, the Capacitor-Coupled Substation with a Controllable Network Transformer (CCS-CNT) emerges as a promising solution. This innovative system leverages the bidirectional capabilities of the Controllable Network Transformer (CNT) to regulate and optimize power flow between high-voltage (HV) transmission lines and local distribution networks [5]. The CCS-CNT system is designed to address the challenges of conventional distribution transformers, which are typically unidirectional and lack the flexibility to efficiently manage power flow in both directions [6]. This capability is particularly critical in modern grids, where power can flow from distributed generation sources, such as microgrids and renewable energy installations, back to the main grid [7] [8]. The energy balance control in a grid-tiered system, such as the renewable power sources, is critical as unstable output results in fluctuating voltages and frequency [9]. The CCS-CNT system integrates a Capacitor-Coupled Substation (CCS), which provides additional benefits such as voltage regulation, reactive power compensation, and the mitigation of ferroresonance, a phenomenon that can lead to instability and equipment damage in conventional substations [10] [11]. By incorporating these advanced features, the CCS-CNT system enhances the overall reliability and efficiency of power distribution networks, making it a suitable option for rural electrification and other applications where traditional methods fall short. The viability of the planning of new installations and determining the best operating conditions of a power distribution network relies on effective power flow system analysis [12].

This paper delves into the mathematical representation of power flow within the CCS-CNT system, providing a detailed analysis of the interactions between the CCS, CNT, and the connected power grid. The mathematical model is essential for understanding the system's behavior under various operating conditions and for designing control strategies that ensure optimal performance. In addition, a control algorithm is proposed, aimed at dynamically managing power flow to balance load demand, minimize losses, and maintain voltage stability across the network. The algorithm is designed to respond to real-time changes in grid conditions, leveraging the controllable aspects of the CNT to achieve a more resilient and adaptable power distribution system.

2. Mathematical Representation of Power Flow in CCS-CNT

The bidirectional power flow in a CCS-CNT system is fundamentally governed by the relationship between the active and reactive power and the control variables,

including the voltages on the primary and secondary sides of the system, the capacitive reactance of the coupling capacitor, and the phase angle difference between the two voltages [13] [14]. Each of these factors plays a crucial role in determining the direction and magnitude of power flow within the system, making it possible to control power transfer effectively in both directions, from the high-voltage transmission line to the local distribution network and vice versa. This mathematical representation can be simplified in the following flowchart:

- *Start Input System Parameters* ($V_{HV}, V_{tap}, X_c, \delta$);
- *Calculate Action Power* (P);
- *Calculate Reactive Power* (Q);
- *Evaluate Power Flow Direction*:
 - *If $P > 0$, the flow is from the HV system to the CCS;*
 - *If $P < 0$, the flow is from the CCS to the HV system;*
- *Control Power Flow* (*Adjust* V_{HV}, V_{tap}, δ);
- *Repeat or End.*

2.1. Active Power Flow Equation

In this system, the active power P transferred through the coupling capacitor is influenced by the voltage magnitudes on the primary HV side and the secondary side V_{tap} , as well as the phase angle difference between these voltages, is given by:

$$P = \frac{V_1 V_2}{X_c} \sin(\delta)$$

where:

- V_1 and V_2 are the voltages on the primary and secondary sides of the coupling capacitor, respectively.
- X_c is the reactance of the coupling capacitor.
- δ is the phase angle difference between V_1 and V_2 .

2.2. Reactive Power Flow Equation

The reactive power Q is associated with the maintenance of voltage levels within the system and is influenced by the difference in voltage magnitudes between the two sides of the coupling capacitor and is described by:

$$Q = \frac{V_1^2 - V_1 V_2}{X_c} \cos(\delta)$$

This equation shows that reactive power is managed by adjusting the voltage difference and the phase angle δ . These equations demonstrate that by controlling V_1 , V_2 and δ , the CCS-CNT system can provide or absorb reactive power, thereby stabilizing voltage levels in the network and enhancing overall power quality.

3. Bidirectional Power Control Strategy

The use of advanced power electronics technology is said to help generate

electricity efficiently and the power transfer capabilities of a system depend on the converter configuration [15] [16]. The integration of advanced power electronics technology into Capacitor-Coupled Substation (CCS) and Controllable Network Transformer (CNT) systems significantly enhances the efficiency of electricity generation and the power transfer capabilities. The control of bidirectional power flow in a CCS-CNT system centers on the ability to adjust the voltage levels and phase angle (δ) between the primary (V_1) and secondary ($V_2 \approx V_{tap}$) sides of the transformer. The control strategy involves:

- Adjusting δ to control the direction of active power flow:
 - If δ is positive, the active power flows from the primary to the secondary side during power tapping.
 - If δ is negative, the active power flows from the secondary to the primary side during power injection.
- Adjusting V_1 and V_2 to control the magnitude of both active and reactive power. By finely tuning V_1 and V_2 the system can regulate the amount of power being transferred and ensure that it meets the desired setpoints for both active and reactive power.

Using Equations (1) and (2), the apparent power ($S = P + jQ$), active power and reactive power can be modeled and calculated through MATLAB using code:

```

% Define the variables
V1 = <value>; % Voltage on the primary side
V2 = <value>; % Voltage on the secondary side=Vtap
Xc = <value>; % Capacitive reactance
delta = <value>; % Phase angle difference in radians

% Calculate Active Power (P)
P = (V1 * V2 / Xc) * sin(delta);

% Calculate Reactive Power (Q)
Q = (V1^2 - V1 * V2 * cos(delta)) / Xc;

% Complex Power (S)
S = P + 1j * Q;

% Display the results
disp('Active Power (P):');
disp(P);
disp('Reactive Power (Q):');
disp(Q);
disp('Complex Power (S):');
disp(S);

```

In this code, you can replace <value> with the actual numerical values for V_1 , V_2 , X_c and δ . The code calculates the active power P , reactive power Q , and the complex power S based on the given formula. Run the code, to get the results. The direction of the power flow will be determined by the phase angle difference value.

Bidirectional Power Flow Control Mathematical Representation

In a Capacitor-Coupled Substation (CCS) system integrated with a Controllable Network Transformer (CNT), achieving bidirectional power flow is essential for efficient operation, especially in scenarios where power needs to be both tapped from a high-voltage (HV) line and injected back into the grid from a lower voltage level. The mathematical representation of bidirectional power flow control is developed through different stages. The system parameters are chosen. The following are the chosen parameters:

- **High-Voltage (HV) Line:** Operating at a voltage level of $H_{HV} = 132$ kV, this line serves as the primary source of power.
- **Tapped Voltage:** $V_{tap} = 11$ kV, representing the voltage level at the point where power is tapped or injected.
- **Controllable Network Transformer (CNT):** This transformer allows for bidirectional power flow, with a tap-changing capability to manage voltage levels.
- **Capacitor Bank:** Provides reactive power compensation and supports voltage tapping by supplying capacitive reactance.
- **Load:** P_{load} = Active Power, represents the active power demand.
- **Microgrid (MG):** Interconnected at the tap voltage level, capable of generating or absorbing power, thereby contributing to bidirectional power flow.

The active power flow of the system can occur in two primary modes: tapping mode (HV to LV) and injection mode (LV to HV).

- **Active Power Flow from HV to LV is given by:**

The power flow equations are developed as:

Active Power Flow from HV to LV (tapping mode):

$$P_{tap} = \frac{V_{tap}^2}{Z_{tap}} \cos(\theta_{tap}) - P_{loss}$$

where:

- V_{tap} is the voltage at the tap point;
- Z_{tap} is the impedance of the transformer tap;
- θ_{tap} is the phase angle of the tap voltage;
- P_{loss} is the power losses in the transformer and line.
- **Active Power Flow from LV to HV (injection mode):**

$$P_{inj} = P_{MG} - P_{loss}$$

where:

- P_{MG} is the power generated by the MG at V_{tap} ;
- P_{inj} is the power injected into the HV line.

The reactive power flow of the system also, can occur in two primary modes: tapping mode (HV to LV) and injection mode (LV to HV).

- **Reactive Power Flow (tap mode):**

$$Q_{tap} = \frac{V_{tap}^2}{Z_{tap}} \sin(\theta_{tap}) + Q_{comp}$$

where:

- Q_{comp} is the reactive power provided by the capacitor bank.
- **Reactive Power Flow (injection mode):**

$$Q_{inj} = Q_{MG} + Q_{comp} - Q_{loss}$$

where:

- Q_{MG} is the reactive power generated or absorbed by the microgrid;
- Q_{loss} is the reactive power losses in the system.

The voltage control is achieved by the CNT adjusting the voltage at the tap node based on the power flow direction and load or MG conditions (whether is it absorbing or injecting power). The voltage at the secondary side of the CNT can be expressed as:

$$V_{tap} = \frac{V_{HV}}{a(t)} \times \frac{1 + jX_c}{1 + jX_{tap}}$$

where:

- $a(t)$ is the variable turns ratio of the CNT, adjusted over time to control the voltage;
- X_c is the capacitive reactance of the capacitor bank;
- X_{tap} is the reactance of the tap.

To control power flow in both directions, the CNT's control algorithm adjusts the tap ratio $a(t)$ and coordinates with the MG and the capacitor bank. The controller maintains the voltage levels within the desired limits and ensures stable bidirectional power flow.

• Tapping Mode

The control strategy for tapping power involves maintaining the V_{tap} close to the desired value while supplying power to the load by adjusting $a(t)$ to minimize the difference between V_{tap} and the reference voltage V_{ref} as follows:

$$a(t) = \frac{V_{HV}}{V_{ref}} \times \frac{1 + jX_{tap}}{1 + jX_c}$$

• Injection Mode

The control strategy for injecting power involves ensuring that the MG power is injected into the HV line with minimal losses by adjusting $a(t)$ based on the desired injection power P_{inj} and voltage level at the HV side as follows:

$$a(t) = \frac{V_{ref}}{V_{tap}} \times \frac{1 + jX_c}{1 + jX_{tap}}$$

where V_{ref} is set based on the desired injection conditions.

• Stability Considerations

The stability of the system is maintained by ensuring that ferroresonance suppression and reactive power compensation is effectively managed. The stability condition is maintained by:

$$\frac{V_{tap}}{V_{HV}} \leq a_{ref}$$

where a_{ref} is the maximum turns ratio for stability.

This mathematical representation and control strategy enables the CCS-CNT system to efficiently manage bidirectional power flow, ensuring reliable operation while adapting to varying load and microgrid conditions.

4. CCS-CNT Control Algorithm Development

The control algorithm for managing bidirectional power flow in a Capacitor Coupled Substation-Controllable Network Transformer (CCS-CNT) system is a critical component for ensuring stable and efficient operation. This algorithm aims to maintain desired power flow conditions by dynamically adjusting control parameters. Below is a detailed discussion of the algorithm.

4.1. Initialization

The control process begins with the initialization phase, where key parameters are set:

- The desired active power (P_{set}) and reactive power (Q_{set}) setpoints are established based on operational requirements and system specifications. These setpoints represent the target values for active and reactive power that the system aims to achieve.
- The initial values for the control variables (V_1), (V_2) and (δ) are set using historical data or initial estimates. These initial values provide a starting point for the control algorithm to operate effectively.

4.2. Measurement of Actual Power Flows

- Using estimation techniques, measure the actual power (P_{meas}) and reactive power (Q_{meas}). These measurements provide feedback on the current state of the system and are essential for adjusting control parameters.

4.3. Error Calculation

To correct any deviations from the desired setpoints:

- Calculate the error between setpoints and measured values. These errors between the desired and actual power flows are calculated using:

$$e_p = P_{set} - P_{meas}$$

$$e_Q = Q_{set} - Q_{meas}$$

where:

- e_p is the active power error and e_Q is the reactive power error.

These errors represent the amount by which the actual power flow deviates from the setpoints and are used to determine the necessary adjustments.

4.4. Controller Design

A Proportional-Integral-Derivative (PID) controller is used to adjust the control variables based on the calculated errors:

- PID controller to adjust V_1 , V_2 and δ is designed using:

$$\Delta V_1 = K_{p1}e_p + K_{i1}\int e_p dt + K_{d1}\frac{de_p}{dt}$$

$$\Delta V_2 = K_{p2}e_Q + K_{i2}\int e_Q dt + K_{d2}\frac{de_Q}{dt}$$

$$\Delta \delta = K_{p3}e_p + K_{i3}\int e_p dt + K_{d3}\frac{de_p}{dt}$$

where:

- K_{p1}, K_{p2} and K_{p3} are the proportional gains.
- K_{i1}, K_{i2} and K_{i3} are the integral gains.
- K_{d1}, K_{d2} and K_{d3} are the derivative gains.
- Update control variables by adjusting them as follows:

$$V_1 \leftarrow V_1 + \Delta V_1$$

$$V_2 \leftarrow V_2 + \Delta V_2$$

$$\delta \leftarrow \delta + \Delta \delta$$

This updating process ensures that the control variables are continuously refined to reduce errors and achieve the desired power flow conditions.

5. Application to a CCS-CNT System

In the CCS-CNT system, the following parameters are considered:

- V_{HV} : High-voltage supply (132 kV);
- V_{tap} : Tap voltage (11 kV);
- V_{load} : Voltage at the load;
- I_{HV} : Current on the high-voltage side;
- I_{tap} : Current on the tap side;
- P_{set} : Desired active power setpoint;
- Q_{set} : Desired reactive power setpoint;
- δ : Phase angle difference;
- X_c : Capacitive reactance of the coupling capacitor;
- Z_{load} : Load impedance.

5.1. Power Flow Calculation

To control power flow within the CCS-CNT:

- Use equation (1) and (2) to compute the power flow based in the system parameters.
- The control logic for the tap voltage requires adjustment of V_{tap} using a proportional control strategy to maintain the desired tap voltage:

$$\Delta V_{tap} = K_{p1} \times (V_{tap,set} - V_{tap,meas})$$

- For power flow control, V_1 , V_2 and δ are adjusted to meet the power flow setpoints:

$$\Delta V_1 = K_{p2} \times e_p$$

$$\Delta V_2 = K_{p3} \times e_Q$$

$$\Delta\delta = K_{p4} \times e_p$$

- The new control variables are then updated as follows:

$$V_{1,new} = V_1 \times \Delta V_1$$

$$V_{2,new} = V_2 \times \Delta V_2$$

$$\delta_{new} = \delta \times \Delta\delta$$

- Determine the direction of the power flow based on the updated variables.

If $P_{flow} > 0$ on the HV side and $P_{flow} < 0$ on the tap node, power is flowing from the HV side to the CCS. Conversely, if $P_{flow} < 0$ on the HV side and $P_{flow} > 0$ on the tap node, power is flowing from the CCS side to the HV network.

This control algorithm ensures that the CCS-CNT system operates efficiently and meets the desired power flow conditions, while also maintaining stability and reliability in the grid.

5.2. Power Flow Control MATLAB Code Verification

The power flow direction within the CCS-CNT can be verified through a MATLAB code approach to prove the viability of the claim of power flow direction in Section 5.1.

```

% Initialize system parameters
V_HV = 132e3; % High-voltage supply in volts (132 kV)
V_tap_set = 11e3; % Desired tap voltage (11 kV)
V_tap_meas = 11e3; % Measured tap voltage
I_HV = 0; % Initialize current on the HV side
I_tap = 0; % Initialize current on the tap side
P_set = 0; % Desired active power setpoint
Q_set = 0; % Desired reactive power setpoint
delta = 0; % Phase angle difference (in radians)
X_c = 0; % Capacitive reactance of the coupling capacitor
Z_load = 0; % Load impedance

% Control gains for proportional control
Kp1 = 0.1; % Proportional gain for tap voltage control
Kp2 = 0.05; % Gain for active power control
Kp3 = 0.05; % Gain for reactive power control
Kp4 = 0.01; % Gain for phase angle control

% Step through the control loop (assuming discrete time steps for control)
for t = 1:100 % Run for 100 time steps
    % Compute the error between the desired and measured tap voltage
    e_Vtap = V_tap_set - V_tap_meas;

    % Adjust the tap voltage
    delta_Vtap = Kp1 * e_Vtap;
    V_tap_meas = V_tap_meas + delta_Vtap; % Update tap voltage

```

Continued

```

% Compute power flow errors (P_set - actual power)
% Assuming basic power flow equations for this calculation
e_P = P_set - (V_HV * I_HV * cos(delta)); % Active power error
e_Q = Q_set - (V_HV * I_HV * sin(delta)); % Reactive power error

% Adjust control variables for power flow control
delta_V1 = Kp2 * e_P;
delta_V2 = Kp3 * e_Q;
delta_delta = Kp4 * e_P;

% Update system voltages and phase angle
V_1_new = V_HV * (1 + delta_V1);
V_2_new = V_tap_meas * (1 + delta_V2);
delta_new = delta * (1 + delta_delta);

% Calculate power flow on HV and tap sides
P_flow_HV = V_HV * I_HV * cos(delta_new);
P_flow_tap = V_tap_meas * I_tap * cos(delta_new);

% Determine power flow direction
if P_flow_HV > 0 && P_flow_tap < 0
    disp('Power is flowing from HV side to CCS');
elseif P_flow_HV < 0 && P_flow_tap > 0
    disp('Power is flowing from CCS to HV side');
end
end

```

The gains and setpoints of active and reactive power can be modified as per the system requirements.

6. Conclusion

The mathematical representation and control strategy for bidirectional power flow in a Capacitor-Coupled Substation with a Controllable Network Transformer (CCS-CNT) system effectively illustrate the system's capability to manage both active and reactive power. By fine-tuning key parameters such as voltage levels and phase angle differences, the CCS-CNT system can dynamically adjust to varying power demands, ensuring stability and efficiency in power distribution networks. The proposed control algorithm, which systematically addresses the challenges of power flow control, provides a robust framework for optimizing power distribution, particularly in scenarios involving renewable energy integration and rural electrification. The findings underscore the potential of CCS-CNT systems as a transformative solution for modern power distribution networks, offering enhanced flexibility and reliability over conventional methods.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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