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Study of Capacitor Coupled Substation with Controllable Network Transformer for Power Tapping and Control

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ABSTRACT

Electricity is indispensable worldwide, but conventional distribution networks struggle in sparsely populated areas. Capacitor Coupled Substations (CCS) and Controllable Network Transformers (CNT) are promising solutions for supplying electricity to such regions. CCS efficiently delivers power to remote areas, while CNT enables bidirectional power flow, crucial for integrating micro-grids and managing energy fluctuations. Combining CCS and CNT facilitates both power tapping and injection into the transmission network. A study using MATLAB/Simulink models the impact of CCS-CNT integration on transmission networks. Results indicate negligible voltage level disturbance, suggesting its seamless integration. Moreover, incorporating CNT within CCS systems might obviate the need for external ferroresonance suppression circuits (FSC). Thus, CCS-CNT systems offer dual functionality, effectively supplying and injecting electricity into the grid while potentially serving as FSCs. The research purpose is to assess the results that can be achieved when utilizing a CCS-CNT system for supplying electricity to a dedicated load. The results showed that a typical CCS-CNT results in normally acceptable output voltage when the system is connected to a

transmission network. Furthermore, it also shows that there is no impact on the transmission network it is connected to. This research underscores the importance of innovative solutions like CCS-CNT in extending reliable electricity access to underserved areas and enhancing grid resilience. Further analysis is warranted to explore additional benefits and optimize system performance.

INDEX TERMS: Capacitor Coupled Substation; Controllable Network Transformer; System Modeling; Electrical Transmission Network; Rural Electrification Technology; Alternative Distribution Network

I. INTRODUCTION

The conventional electricity supply from an electricity generation plant to the consumers follows a known sequence flow which includes, the process where the electricity generation plant generates electricity at a particular voltage, the voltage is stepped up to the transmission network, thereafter, the transmission network transmits electricity to distant areas where it is then stepped-down to distribution network voltages for customer consumption [1] [2]. This process requires the development of both the transmission and distribution infrastructure.

However, developing a distribution network infrastructure in sparsely populated areas where the consumption may be too low, the system is deemed to be uneconomical [3] [4]. This is partly due to the fact that irrespective of the load size, the infrastructure should still take into consideration the transmission and distribution assets such as transmission lines, power transformers, protection devices, substation equipment and auxiliary structure [5]. Different technologies are thus required to ensure that electricity can be supplied to the sparsely populated areas cost-effectively [6].

Capacitor Coupled Substation (CCS) is one of the technologies that can be used for supplying electricity to sparsely populated areas [7]. Furthermore, most sparsely populated areas have a vast amount of empty land that can benefit from the new technologies of micro-generation plants that may include photovoltaic plants [8]. To fully benefit from the advantage of these new technologies and the availability of open land, technologies to allow micro-generation plants to generate electrical power and be able to feed it into the transmission grid requires consideration [9] . Power flow control can be effected through numerous systems such as the Controllable Network Transformers (CNT) [10].

The focus of this paper is therefore to develop, model and simulate a Capacitor Coupled Substation with a Controllable Network Transformer for power flow control (CCS-CNT) system that can be used for bi-directional power flow control. This bi-directional power flow control can be used to supply electrical power from the High Voltage (HV) transmission network through the CCS and to also supply electrical power into the HV transmission network through the CCS-CNT system. This novel configuration utilizes the CCS technology which currently gets consideration for tapping electrical power from HV lines to distribution medium voltage (MV) levels through coupling capacitors. Similarly, the CCS can also be used to inject electrical power from any electricity source back into the HV lines. To allow this application to be effected, a bi-directional electrical power flow system is required. It is with this in mind that a CNT can be incorporated into the CCS to allow for controllable bidirectional electrical power flow from or into the HV transmission lines. The CNT works both as a distribution transformer for HV to MV voltage requirements and also as a control apparatus for LV to HV voltage transformation.

Although CCS has been studied by various scholars, its practical implementation has been limited. Similarly, the CNT has been studied by a few scholars [11] [12] [13] [14], however, its practical implementation has been limited. This paper, therefore, uses MATLAB/Simulink software to model and simulate a CCS-CNT system so as to gain knowledge that can assist in understanding the basic functionality of a CCS-CNT and its adoptability to a typical transmission network that has a 400kV/11kV CCS connected to it.

II. THEORETICAL BASIS

The basis of the proposed CCS-CNT model is based on a combination of a CCS and a CNT. The CCS being a vastly studied alternative system for distribution of electricity to sparsely populated areas use the principle of a Capacitive Voltage Transformer (CVT) to tap electricity from HV transmission line and convert it to MV levels without the use of conventional transmission-to-distribution infrastructure [15] [16]. The CNT employs a modified Load Tap Changing (LTC) transformer to control the voltage levels through the use of a Thin AC Converter (TACC) [17].

A. Capacitor Coupled Substation (CCS)

A CCS is an infrastructure that can be used for tapping electrical power from HV lines to medium distribution voltages through coupling capacitors without the need for complex transmission-to-distribution network infrastructure. A CCS can be relatively small and be located near or directly underneath HV transmission lines for the purpose of dedicated power supply to dedicated areas [18]. This technology is said to be one of the co-effective systems that can be adopted for supplying electricity to sparsely dedicated areas [19]. Figure 1 presents a simplified depiction of a CCS.

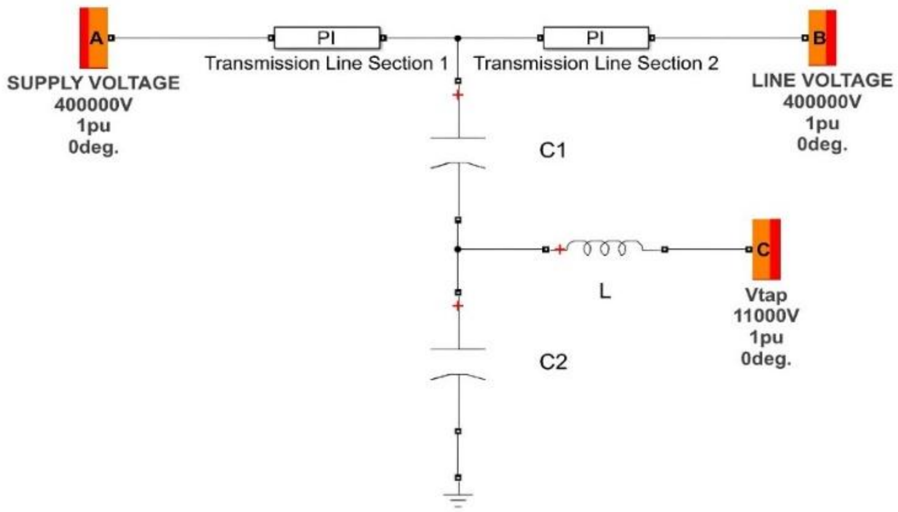

Figure 1: Simplified CCS

Figure 1 shows a typical simplified CCS where Bus A and Bus B represent the transmission line upstream and downstream of the CCS tap node. C_1 and C_2 represent the coupling capacitor banks and Bus C represents the tap voltage which is the desired medium voltage for further distribution to the consumer load system. The distribution transformer is connected on Bus C. The tap voltage can be expressed in terms of the input voltage (V_{in}) and the quotient of the capacitor divider (C_1) and the equivalent Thévenin capacitor (C_1+C_2) as presented in equation (1).

$$V_T = V_{in} \times \frac{C_1}{(C_1+C_2)} \quad (1)$$

Figure 2 depicts the Simulink model for a typical CCS. The model is used to simulate the stand-alone CCS connected to a transmission network and supplying a fixed load through a standard distribution transformer.

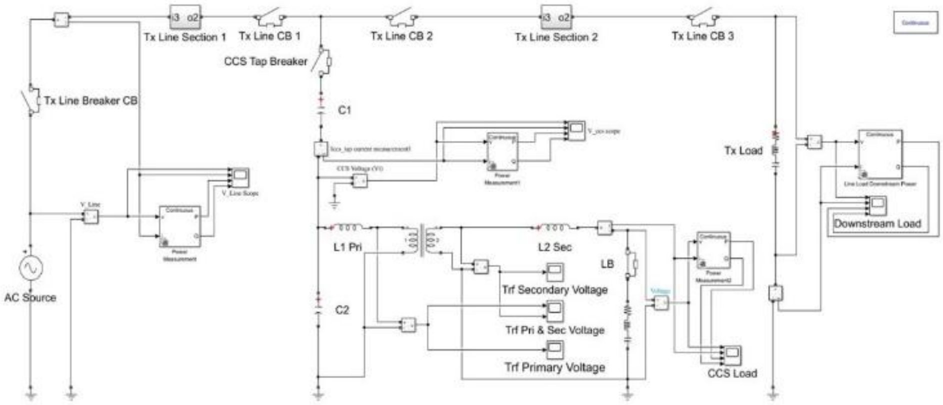

Figure 2: Basic CCS Model

Figure 2 illustrates the MATLAB/Simulink model used for the simulation and modeling of a CCS. The AC source represents the upstream of the transmission network. The CCS is located at a particular distance between line section 1 and line section 2. The step-down transformer steps down the tapped voltage of $11kV$ to the consumer voltage level of $400V_{ac}$. A CCS forms one part of the CCS-CNT system.

B. Controllable Network Transformer (CNT)

A CNT basically controls the output voltage by controlling the amplitude and phase angle of the voltage. The CNT can be configured to work with an already market available LTC transformers by an addition of a functionally rated alternating current (AC) converter [20]. A CNT provides a simultaneous control of bus voltage magnitudes, phase angles and line currents by augmenting an LTC with a small, rated converter where conventional techniques are deemed ineffective [11] [21]. The control of both the bus voltage and phase angle is achieved through the use of a dual virtual quadrature sources (DVQS) for power flow control in a meshed network [12]. A standard CNT is illustrated in Figure 3.

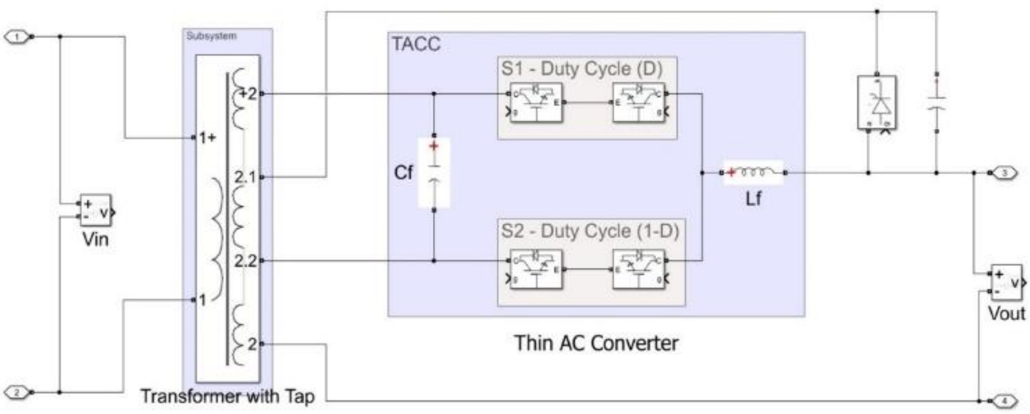

Figure 3: Basic CNT Representation

The output voltage (V_{out}) can be expressed in terms of the input voltage (V_{in}), the duty cycle (D) and the tap ratio (n) as presented in equation (1).

$$V_o = \left[\frac{D}{1+n} + \frac{1-D}{1-n}\right] V_{in} \tag{2}$$

A CNT allows for smooth power flow control in both directions and also has an advantage over other power flow controllers due to its ability to independently control each phase of a three-phase system. It also operates on a "fail normal" mode where in the case of any failure on the converter, it can operate as a normal LTC by bypassing the semiconductor switches [12].

A MATLAB/Simulink model of a typical CNT is presented in Figure 4.

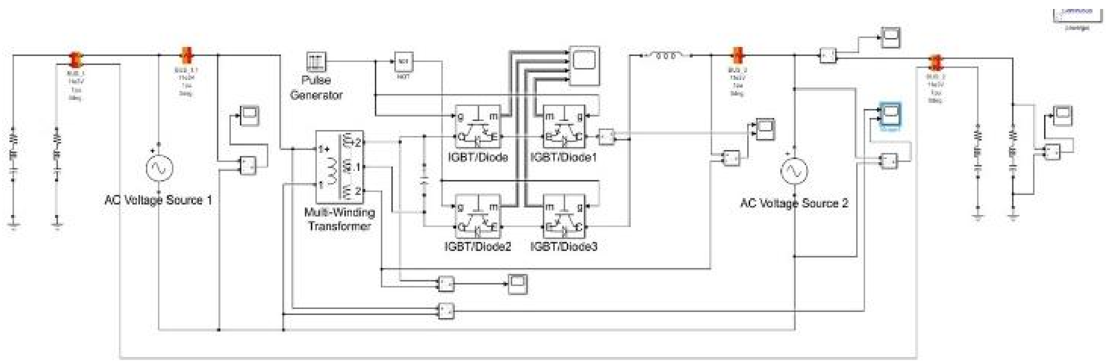

Figure 4: Basic CNT Simulink Model

C. Proposed Capacitor Coupled Substation with Controllable Network Transformer (CCS-CNT)

The proposed CCS-CNT model comprises of a standard CCS with the distribution transformer being replaced by an LTC that is further incorporated into a CNT. Figure 5 illustrates the block diagram for the CCS-CNT system.

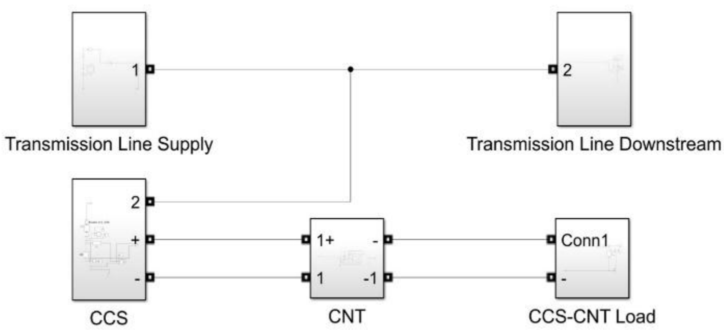

Figure 5: CCS-CNT Block Diagram

Figure 5 illustrates the CCS-CNT block diagram that presents a combination of a CCS and a CNT connected while Figure 6 illustrates the MATLAB/Simulink Model used for the simulation of a CCS-CNT.

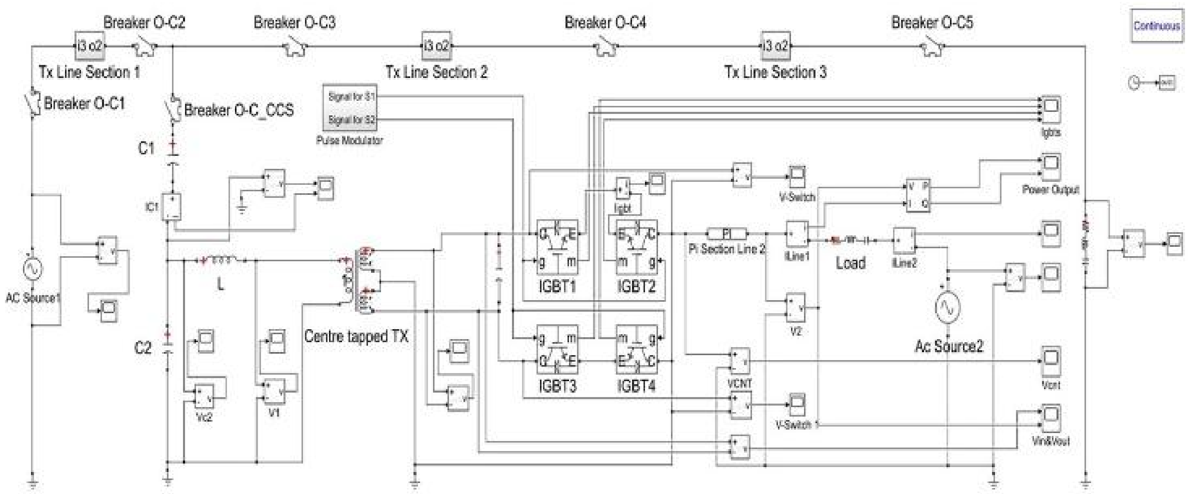

Figure 6: CCS-CNT Model

The development of micro-grids results in increased system loads and level of penetration which require flexible transmission systems [22]. CNT is one of the systems that is flexible and able to independently control active and reactive power [23]. By adopting a CNT incorporated into a CCS, the CCS-CNT can be used for power tapping to supply electricity to remote areas while being able to inject electricity back into the transmission network in the event of those remote areas developing microgrids. This is feasible as the CNT does not have to operate at the transmission level voltages but only limited to medium voltage levels, which is a technology that has been studied extensively [13] [11] [24] [25].

III. METHOD

The basis of the CCS-CNT operation is primarily based on the functioning of a CCS and that of a CNT. The method for simulating a CCS-CNT requires an observation of the system behavior under CCS operation and also the behavior of the system with a typical CNT as the power control system. In this paper, a CCS, a CNT and thereafter a CCS-CNT is simulated. The parameters used for the simulation of the CCS are presented on Table 1.

Table 1: CCS Simulation Parameters

Parameter	Value	Source
V_s	400kV rms	Selected Transmission Line
V_T	11kV rms	Selected Tap Voltage
CCS Load	400 V rms, 50Hz, 80kW, 0.8PF	Selected load value
Downstream Load	400kV rms, 50Hz, 50MW	Selected load value
CCS Transformer	11kV/400V	Selected Transformer
C_1	0.1231 µF	Capacitor Bank 1
C_2	7.5 µF	Capacitor Bank 2
L	1mH	Line Inductance
Tx Line Section #1	300km	Selected
Tx Line Section #2	300km	Selected

The parameters in Table 1 are used for simulation of the model illustrated in Figure 2 to observe the transmission line response when a CCS-CNT is connected to the transmission system. The supply voltage, transmission line downstream voltage, CCS distribution transformer primary and secondary voltages are observed. The simulation presents a time domain fixed time representation, and it does not take into consideration internal parameters of the entire system.

IV. RESULTS AND DISCUSSION

Each sub-system individual simulation results are presented in the sub-sections below.

A. CCS Simulation Results

When parameters in Table 1 are used in the model in Figure 2, the resulting representation is illustrated in Figure 7, Figure 8, and Figure 9. For the purpose of observing the system behavior, the CCS circuit breakers were switched ON and OFF at known intervals and the resulting outcome is illustrated in Figures 7, Figure 8, and Figure 9. Figure 7 and Figure 8 show the distribution transformer primary and secondary voltages of 11kVrms and 400Vrms.

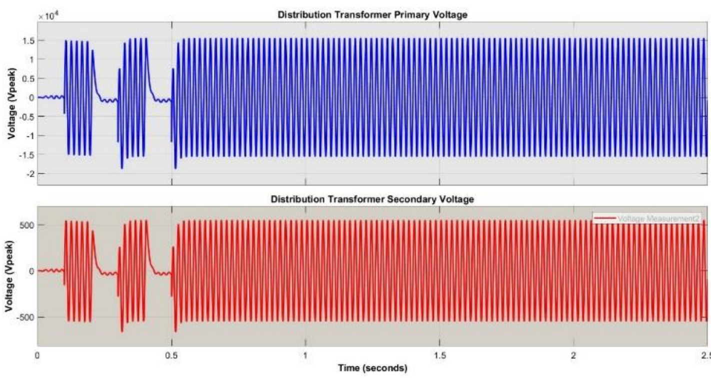

Figure 7: Distribution Transformer Primary and Secondary Voltage

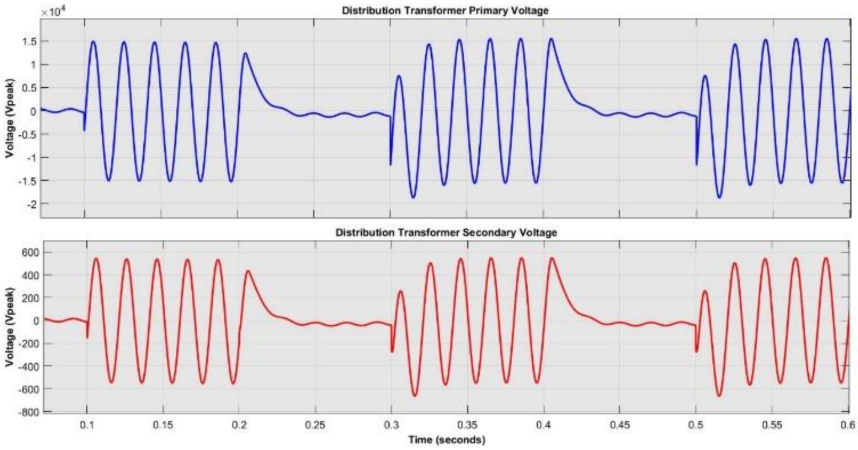

Figure 8: Distribution Transformer Primary and Secondary Voltage

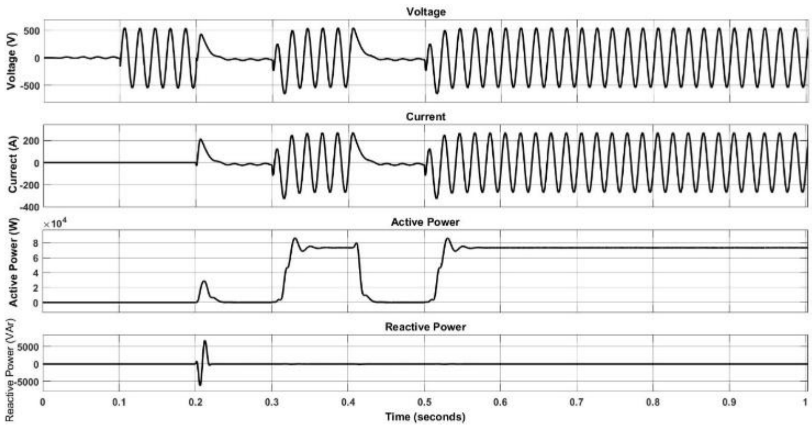

Figure 9: CCS Load Parameters

These results can be validated through the comparison of the simulated values and the calculated value. The calculations are simplified to only focus on the supply voltage (V_s) and the tap voltage (V_{TAP}). Using (1) and parameters on Table 1, the resulting voltages are calculated as:

$$V_{T(rms)} = V_{in} \text{ x } \frac{C_1}{C_1 + C_2} = \ 6\ 459.31\ V$$

$$V_{T(peak)} = V_{rms} \text{ x } \sqrt{2} = 9\ 134.84\ V$$

$$V_{T(3\varphi)} = \ V_{peak\ (1\varphi)} \text{ x } \sqrt{3} = 15\ 822\ V$$

For comparison, the measurement of Figure 8 is illustrated in Figure 10, and it shows V_{TAP} on value #1 as 1.558e+04 = 15 583 V ≈ to the calculate 15 822 V.

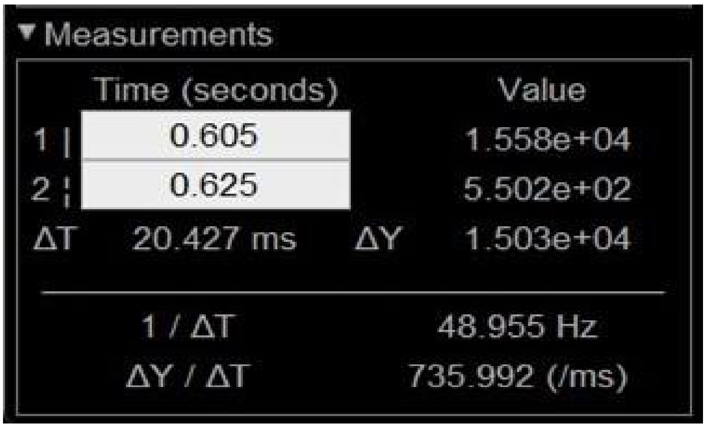

Figure 10: Figure 8 Measured Values

Similarly, the distribution transformer secondary voltage is given in Figure 10 as value #2 = 5.502e+2 = 553.20 V ≈ to the calculate 565.68 V. Therefore, it can be firmly asserted that the result achieved through simulation are congruent to the calculated value for the CCS model used.

B. CNT Simulation Results

The CNT's main purpose is to maintain the output voltage as a constant value when located between two bus systems. Figure 11 illustrates a basic CNT simulation input and output voltages.

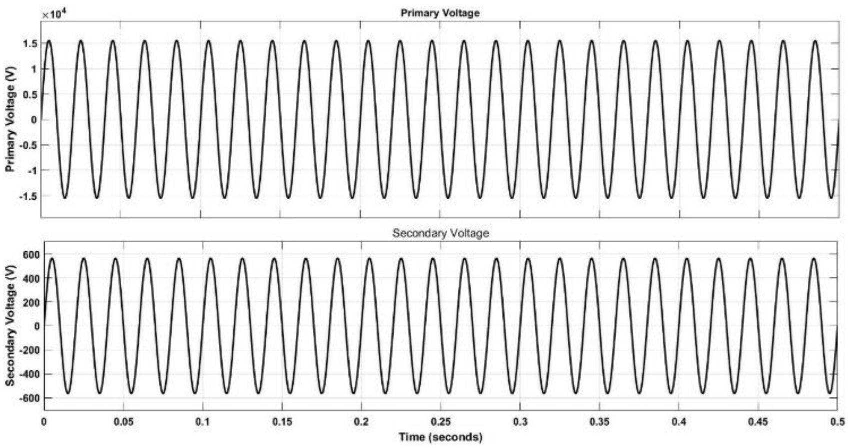

Figure 11: CNT Primary and Secondary Voltage

Figure 11 illustrates the results of a CNT system that has $11kV_{rms}$ bus 1 connected to a $11kV_{rms}$ bus 2 as presented in Figure 4. Bus 1 voltage is at 0-degree phase angle and bus 2 is at 15-degree phase angle so that the two buses are at the same potential but different phase angles. The principle of power flow between two buses is similar to the principle of parallel operation of synchronous machines where there would be no power flow if the two parallel machines have equal power. The phenomenon is represented by the difference in the voltage phase angles in the case of the two buses for the CNT to allow power flow between them [26].

The CNT maintains the output voltage levels through the switching of the insulated-gate bipolar transistor (IGBTs). The IGBTs are triggered using a pulse generator. The output voltage is maintained by the pulse applied to the gates of the IGBTs. Figure 12 illustrates the IGBT switch currents and switch voltage.

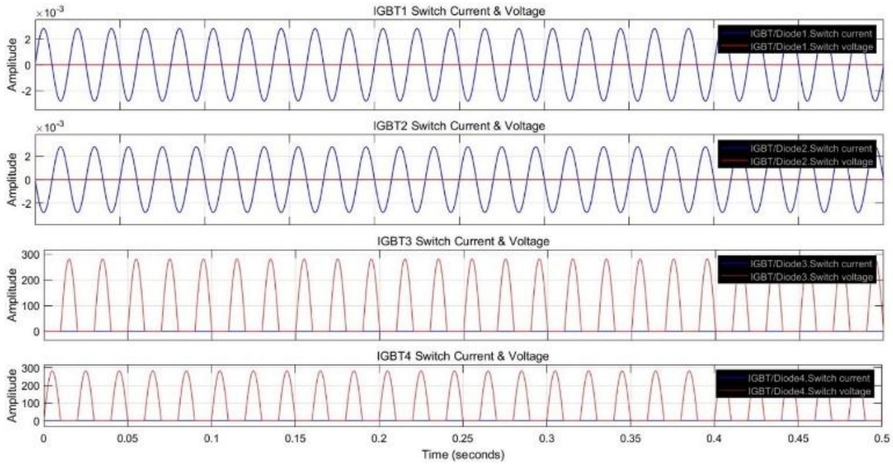

Figure 12: IGBT Switch Current and Voltage

Figure 12 representing the IGBT switch current and voltage shows that when IGBT 1 switch current is positive, the corresponding IGBT 4 voltage is also positive and when the IGBT 2 current is positive, the corresponding IGBT 3 voltage is positive. Therefore, at any point in time, whether switch 1, represented by IGBT1-IGBT4 or switch 2 represented by IGBT2-IGBT3 is switched ON/OFF, the overall output voltage is kept positive. This simulation used a pulse generator to represent the input pulse. However, in a practical application, the pulse signal amplitude is controlled by the value of the output voltage feedback loop in order to achieve the desired actual output voltage.

C. CCS-CNT Simulation Results

When parameters in Table 1 are used in the model in Figure 6, the resulting representation is illustrated in Figure 13. One of the pertinent point of when assessing the CCS-CNT system is to observe if there is any direct impact on the main transmission network, which is represented by the voltage source in the simulation model, when a CCS is switched ON. Figure 13 shows that the supply voltage or the upstream voltage value does not get affected when the CCS system is switched ON.

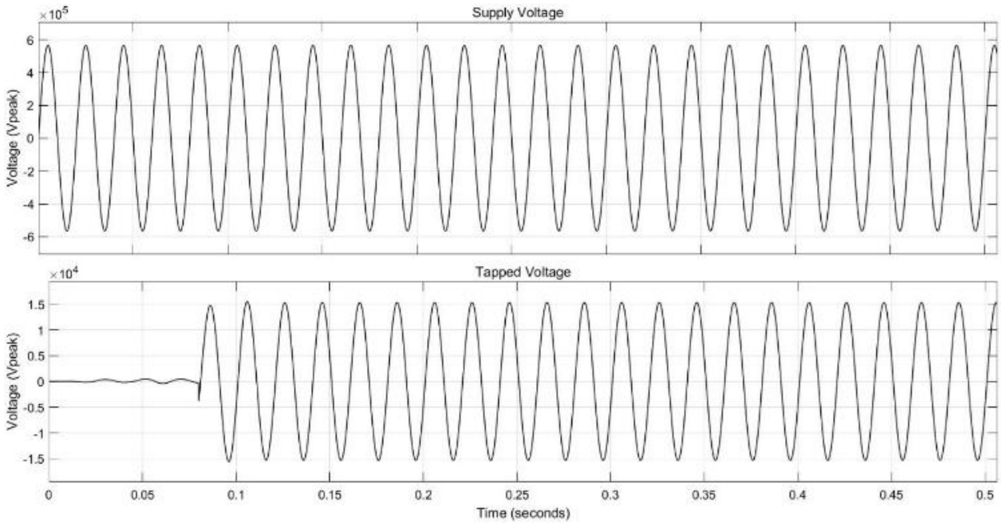

Figure 13: Supply and Tapped Voltage

Figure 13 shows that when the CCS-CNT system is switched ON at time (*T=0.08* seconds), the supply voltage does not get affected with the tapped voltage at 15.56kV$_{(peak)}$ and supply voltage remaining steady at 565kV$_{(peak)}$.

Figure 14 illustrates the IGBTs switch current and voltages. It shows that at any point in time, the two switched IGBTs have positive voltage, allowing them to maintain the desired output voltage. For the IGBT to stay in the ON position and allow the current flow, the pre-set voltage must be maintained. As shown in Figure 15, when IGBT 1 voltage goes to a negative value, IGBT 2 voltage goes to positive in order to keep the IGBT1 and 2 switch above the designed positive voltage to allow a continuous output, thus maintaining the CNT output voltage at a desired value as illustrated in Figure 16 and Figure 17.

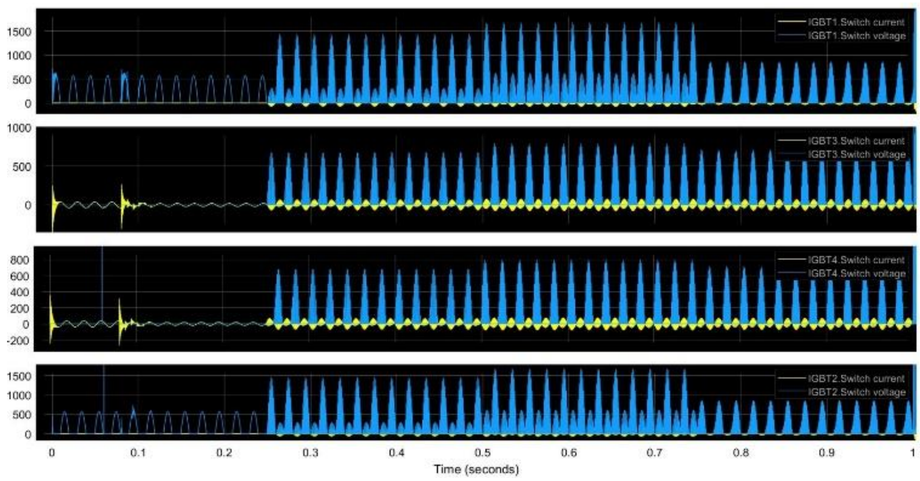

Figure 14: IGBTs Switch Current and Switch Voltage

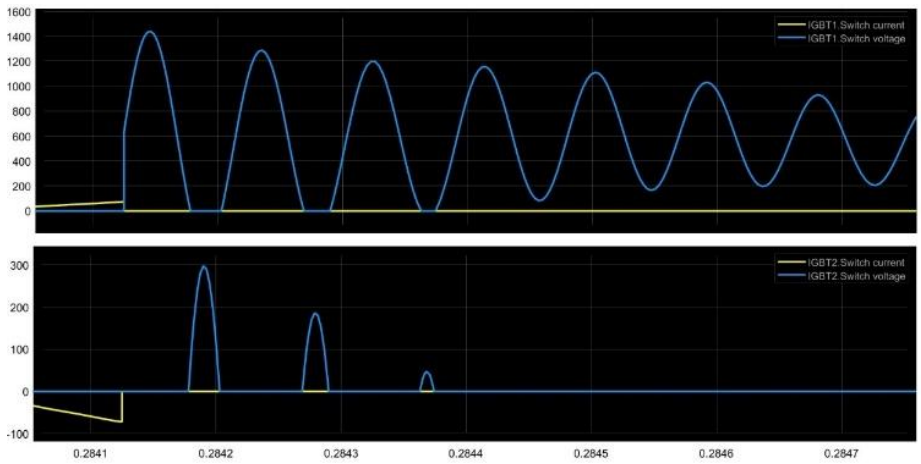

Figure 15: IGBT 1 and IGBT 2

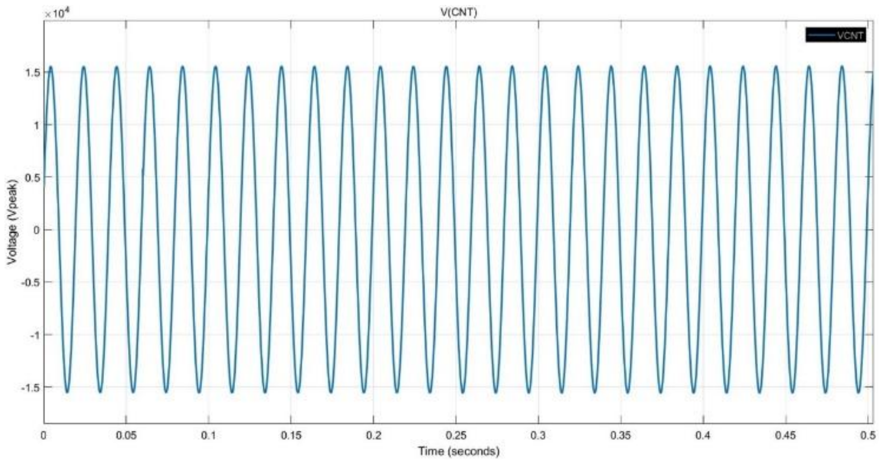

Figure 16: V-CNT

V. CONCLUSION

The development of a CCS-CNT requires an assessment of both a CCS and a CNT individually and thereafter as a single system. The objective of this article was to simulate a CCS-CNT on a transmission network to observe if there is any impact on the transmission network when the system is connected. The results show that there is no notable impact on the transmission network when the CCS-CNT is connected. Furthermore, the results show that the bus or output voltage can be maintained with the use of a CNT. Therefore, it can be concluded that a combination of a CCS-CNT has an ability to control the bus voltage and further studies can be conducted to establish if it can be used for both power tapping and power injection as the CNT has a bi-directional capabilities. The results further establish a point of focus that can be further analyzed for other applications such as ferroresonance suppression when using a non-linear distribution transformer.

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