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Hybrid LCC-VSC Bipolar HVDC System for DC Power Tapping Studies

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SUMMARY

Line Commutated Converter based High Voltage DC (LCC-HVDC) is the most mature technology of HVDC power transmission globally. In addition to having higher voltage capabilities and higher power levels than Voltage Sourced Converter based HVDC (VSC-HVDC) technology, LCC-HVDC also has lower cost of implementation and lower power losses. On the other hand, VSC-HVDC has technical superiorities over LCC-HVDC such as the possibility of independent control of active and reactive powers, elimination of the risk of commutation failures, and the reduction of harmonic filters sizes. To make the most of both LCC-HVDC and VSC-HVDC technologies, hybrid LCC-VSC HVDC transmission systems are being developed by interfacing existing LCC-HVDC systems with VSC-based technology. LCC-HVDC lines span very long distances which make them suitable for HVDC power tapping through VSC technology. This work develops a comprehensive tapping study system in RSCAD using the RTDS NovaCor real-time simulator. The hybrid system consists of a ±500 kV 3 GW LCC-HVDC bipole system and two DC power tapping stations, with one per pole, connected in parallel with the LCC-HVDC lines at their midway point. Each power tapping station consists of a DC-DC Modular Multilevel Converter (MMC) designed with a high DC voltage step down ratio. The simulator has two main components for the runtime: the processor cores and the GT-FPGA units. The LCC-HVDC Bipole HVDC system was modelled on the processor cores while the MMCs were modelled through both the cores and separate GT-FPGA units. The positive pole tapping station was modelled on the GT-FPGA units using the detailed U5-MMC models and these units also generate the MMC firing pulses. The negative pole tapping station was modelled on the processor cores using the average MMC5 models. The main parameters of the hybrid LCC-VSC Bipole HVDC system were as follows: the LCC-HVDC bipole is rated at 500 kV, 1500 MW per pole and each DC-DC MMC is rated at 75 MW, designed with a 500:40 DC step ratio to create a bipolar ±40 kV MVDC output bus. The controls implemented in this work allowed for independent operation of each tap. Thus, the hybrid LCC-VSC system created provides substantial flexibility for systems level tapping studies, due to independent tapping station operation combined with practical LCC-HVDC controls and operating modes. Simulation results are presented to confirm the feasibility of independent pole power tapping and ability of the LCC-HVDC stations to accommodate both symmetrical and asymmetrical power tapping conditions.

KEYWORDS

Hybrid VSC-LCC HVDC System, Power Tapping, Real Time Simulation

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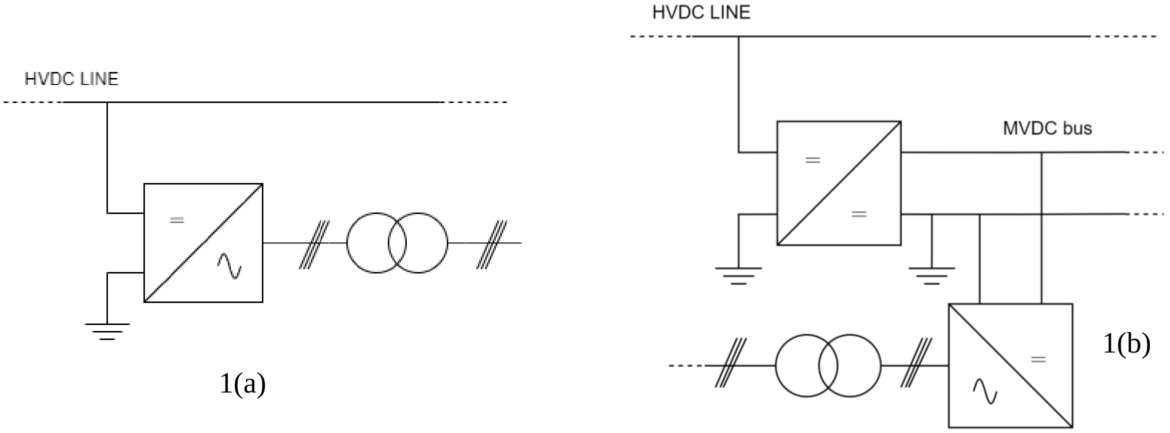
1. Introduction

High Voltage Direct Current (HVDC) transmission systems have been in operation for decades. Some of the benefits of HVDC include: (i) a more efficient bulk power transfer over long distances due to lower losses in DC transmission lines (ii) an easier interconnection of DC networks as compared to asynchronous AC networks, and (iii) improved system stability, reliability, and transmission capacity [1]. The majority of existing HVDC systems are line-commutated converter (LCC) based [2]. These converters have lower costs of implementation and lower power losses as well as high voltage capabilities contributing to higher power levels [3]-[4]. More recently, voltage-sourced converters (VSC) have emerged as the preferred technology mainly due to their several advantages over LCCs, such as no commutation failure risk, increased system stability through reactive power supply and the feasibility of independent active and reactive power control [5]. At present, the most popular type of VSCs used in the HVDC are the modular multilevel converters (MMC) [6]-[7]. MMCs also have several advantages, namely, the ability to satisfy high voltage requirements due to their modularity and scalability, low power losses and relatively small AC filters requirement [7]-[8]. To make the most of both LCCs and VSCs systems, hybrid LCC-VSC transmission systems are being developed [9]-[10]. VSCs are being added to existing LCC-HVDC systems for expansion or for renewable energy integration. Since LCC-HVDC systems span over hundreds of kilometres, HVDC line power tapping has become a major point of interest in the power and energy research field [11]. Power tapping is the removal of a small amount of power (usually ≤ 5% [11]) to transmit power to remote areas and isolated communities. In such applications, VSCs are implemented in parallel (parallel tapping) or in series (series tapping) with existing LCC-HVDC systems through AC or DC tapping [12]-[13]. Over the past few years, several studies have looked at power tapping with different types of converter topologies and systems. However, the majority of research regarding tapping correspond to single-stage AC tapping of LCC systems. In previous studies that have been done on DC tapping, the impact of symmetrical and asymmetrical power tapping on bipole LCC-HVDC systems has not been examined. In [14-16], the CIGRE HVDC benchmark system in PSCAD was used to carry out tapping studies on a monopolar system through either AC tapping or DC tapping. In [13], DC tapping was performed on an LCC bipole system, but the study involved only a single tapping converter installed symmetrically across the two poles. To address this gap in the literature, this work explores DC power tapping on a LCC HVDC bipole using two independent MMC-based tapping stations, modelled on a RTDS NovaCor simulator.

1.1. Concept of DC Tapping

There are two main types of power tapping: AC tapping and DC tapping. The conventional way of power tapping is to simply use a DC-AC converter, also known as AC tapping, as shown in Figure 1(a). AC tapping is a single stage operation.



1(a)

1(b)

Figure 1: Types of Parallel Tapping: 1(a) AC Tapping and 1(b) DC Tapping [17]

In Figure 1(b), DC Tapping uses a DC-DC converter to create an intermediate MVDC bus for added flexibility in power distribution. Downstream DC-AC converters could then be used. DC tapping is also known as two-stage tapping. MVDC voltages and power levels are more suitable for distribution applications in comparison to HVDC systems which are more suited to bulk power transfer over long distances. Thus, a DC-DC converter capable of achieving a high DC step down ratio is required to interface the HVDC link and MVDC bus.

2. Hybrid LCC-VSC Bipole HVDC System Overview

In this study, a hybrid LCC-VSC HVDC bipole system was developed based on a detailed LCC-bipole system, available through RTDS. The LCC bipole is loosely based on the 3-Gorges bipoles in China [18], and in this work is augmented by adding two MMC-based DC-DC converters (each installed at the midway point between LCC stations). The DC-DC MMC is based on high step-down voltage ratio topology known as the M2DC-CT [19]. Figure 2 shows the hybrid LCC-VSC HVDC system.

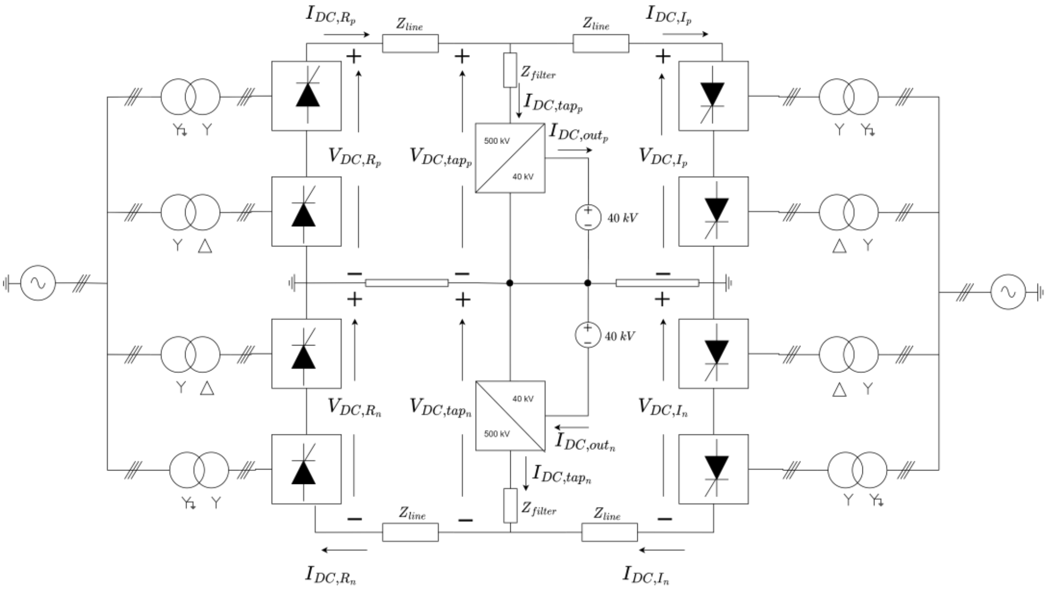


Figure 2: Developed LCC Bipole System with MMC-Based Tapping Stations

2.1. LCC HVDC Bipole System

The main parameters of the hybrid system in Figure 2 are given in table 1.

Table 1: LCC-HVDC Bipole Parameters

Parameters	Description	Value
P_{dc}	DC Power measured at Rectifier	3000 MW
$V_{dc,R}$	Nominal Rectifier DC Voltage	± 500 kV
$v_{ac,R}$	Rectifier side AC line-to-line voltage	525 kV rms
$v_{ac,I}$	Innverter side AC line-to-line voltage	525 kV rms
α	Nominal Rectifier firing angle	15°
γ	Nominal Inverter firing angle	17°
R_{dc}	Single Pole DC line Resistance	4.855 Ω
f	Rectifier and inverter side AC network frequency	50 Hz
I_{dc}	Nominal DC link current	3.0 kA
$I_{dc,margin}$	Nominal DC link current margin	0.3 kA

Each pole is rated at 500 kV, 3 kA (1500 MW). The rectifier and inverter stations both use twelve-pulse LCC configurations. The transformers are all equipped with transformer tap changers to regulate the secondary voltage during different modes of operation. The HVDC link spans 1059.1 km with 60 km and 40 km electrode lines connected to the neutral line at the rectifier and inverter stations respectively. The electrode lines are used for grounding purposes [18].

2.1.1. HVDC Station Controls

The overall control structure of the LCC-HVDC bipole system is given in Figure 3 . I_{dc} and I_{dc0} are the main current inputs while V_{dc0} and V_{dc} are the main voltage inputs. I_{dc0} represents the rectified DC current from the rectifier station while V_{dc0} corresponds to the rectified AC voltage.

Table 2 : LCC-HVDC Control Schemes

Pole αmax Calculation	Involved in current and voltage control
Voltage Control Amplifier (VCA)	Controls voltage when DC link voltage drops below certain threshold
Current Control Amplifier (CCA)	Normally run by rectifier. Inverter runs CCA when current drops by a certain amount
Converter Firing Controls (CFC)	Generates firing pulses
Voltage Dependent Current Order Limit	Reduces current order when low voltages are detected

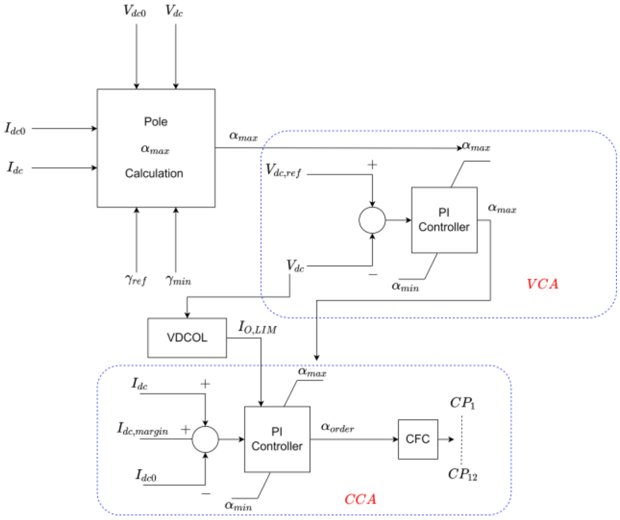


Figure 3: LCC-HVDC Control Scheme for Inverter Station

Table 2 shows the main objectives of the control components of the LCC-HVDC bipole system. Other control components include tap changer controls, power control modes, current order synchronization, current margin compensation and commutation failure protection, as well as AC and DC fault protection. More details on these control algorithms can be found in the RTDS manual [18].

2.2. M2DC-CT Tapping Stations

Table 3 : M2DC-CT Parameters

Parameter	Description	Value
$P_{dc,rated}$	Rated Power of each M2DC-CT	75 MW
V_{dci}	Input DC voltage	500 kV
V_{dco}	Output DC voltage	40 kV
N_p, N_s	Number of SMs in upper and lower arms	460 (FBSM), 40 (HBSM)
L_p	Upper arm inductance	50 mH
L_s	Lower arm inductance	10 mH
C_p	Upper arm SM capacitance	1 mF
C_s	Lower arm SM capacitance	12.5 mF
f	Fundamental frequency	150 Hz

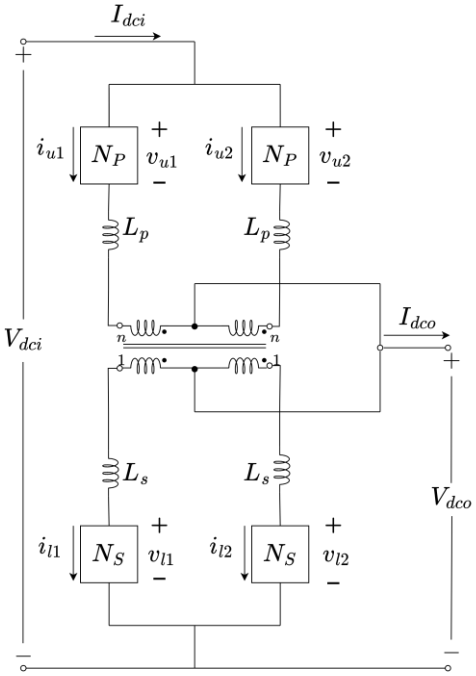


Figure 4 : M2DC-CT used in Figure 2 as MMC based DC-DC Converter [19]

The topology of the M2DC-CT used to realize each DC-DC tapping station is shown in Figure 4 [19]. The parameters for each M2DC-CT are given in Table 3.

The 40 kV output DC voltage value was chosen to reflect envisioned practical MVDC voltage levels [20]. The nominal voltage of each submodule (SM) capacitor is 2 kV. The ratio of the output DC voltage to the input DC voltage is G_v=40/500=0.08. To achieve this voltage ratio, the internal transformer was designed for turns ratio n=11.5:1 (460 kV: 40 kV). Full bridge submodules (FBSMs) are used in the upper arms. This was a design choice to enable fault blocking (through converter gate signal blocking) should the LCC voltage collapse. Half bridge submodules (HBSMs) are used in the lower arms. The rated HVDC tapping current at each M2DC-CT is approximately 0.05×3000=150 A.

The controls for the M2DC-CT are detailed in [19] and includes both output power regulation and internal capacitor voltage balancing.

2.2.1. M2DC-CT Input Filter Design

Initial simulation studies revealed second order (300 Hz) and fourth order (600Hz) harmonic currents flowing into the M2DC-CTs. Although the effects were minimal in the HVDC system, the total harmonic disturbances were relatively high in the M2DC-CTs. As a result, passive filter [11] were implemented at the input side of each M2DC-CT, as illustrated in Figure 5.

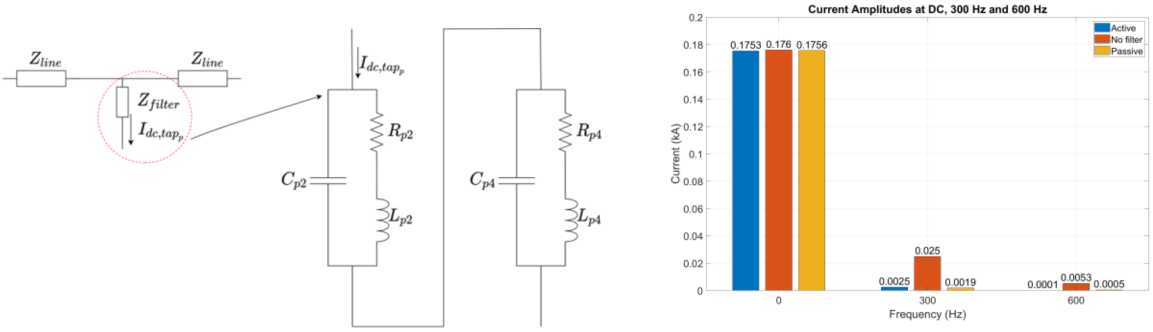


Figure 5 : Input Filter Design and simulated harmonic analysis results

From the simulated harmonic spectra in Figure 5, both active and passive filtering schemes were tested and could provide the required reduction in harmonic currents. However, passive filters were selected to avoid undesirable controller harmonic interactions that could potentially occur between stations.

3. Simulations

Several scenarios were tested. The first scenario involved pre-charging the entire hybrid LCC-VSC HVDC system. After steady state operation was achieved, power tapping studies were carried out at different power demands. $P_{dc,p}$ and $P_{dc,n}$ represent the power demand at the positive and negative pole tapping stations, respectively. The main results for pre-charging operation, symmetrical tapping and asymmetrical tapping are presented.

3.1. Pre-Charging Consideration for Tapping Stations

During the normal energization sequence for the LCC-HVDC bipole, it was found that the capacitor voltage balancing controls for the M2DC-CT needed to be activated. This was needed because of the different number of SMs and different capacitance values in the upper and the lower arm SMs, see Table 3. Consequently, without active controls, the rate of charging the SM capacitors would be different between arms (since arms are in series with a common DC charging current). By activating the arm capacitor voltage balancing controls while $P_{dc,p}$ = $P_{dc,n}$ = 0, the tapping stations were able to properly pre-charge the SM capacitors to the desired 2 kV value, concurrent with normal energization of the LCC-HVDC system. Figure 6 demonstrates the results of the pre-charging operation for the rectifier firing angles, inverter extinction angles, DC currents of both the LCC system and the M2DC-CTs as well as the average capacitor voltages of the SMs in each arm. The repetitive short-term dips occurring in the waveforms are due to changes in transformer tap positions.

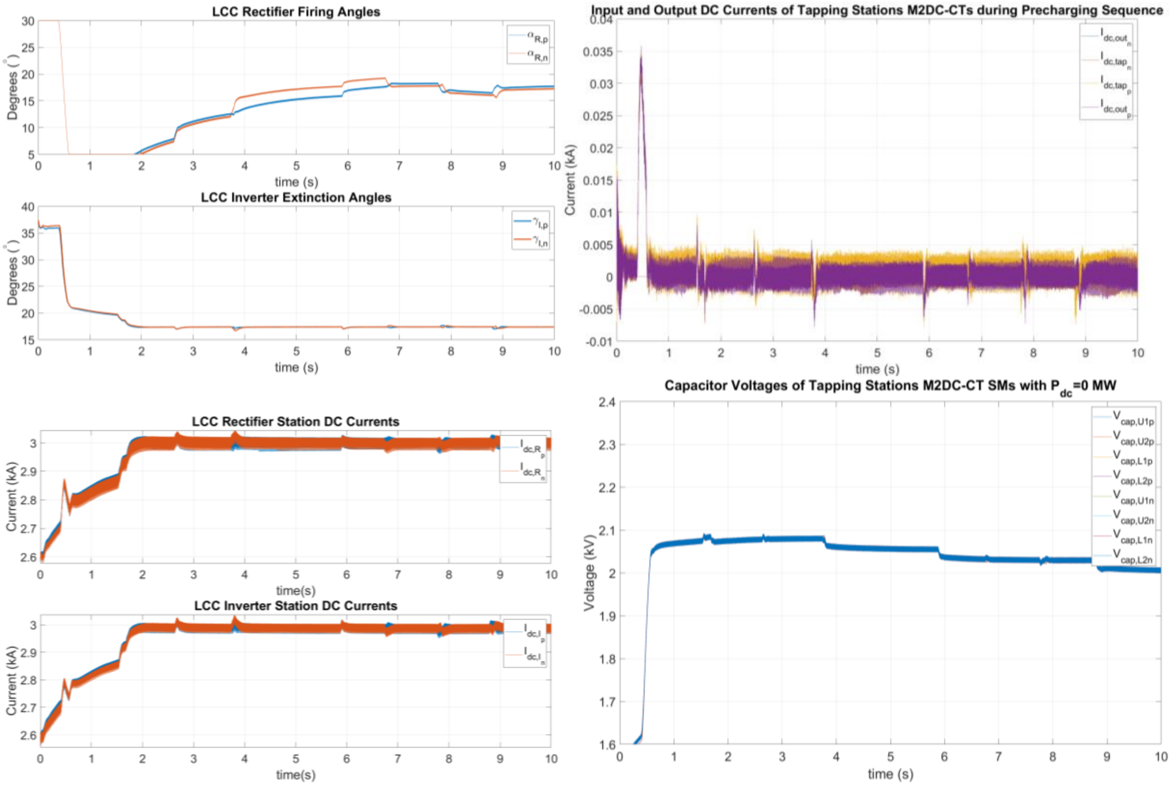


Figure 6: Pre-Charging Results of LCC bipole system and M2DC-CTs

3.2. Symmetrical Power Tapping

During symmetrical power tapping, $P_{dc,p}$=$P_{dc,n}$. The power demand had three instances of change:

- At t=1s, power demand increased from 0 MW to 37.5 MW at a rate of 750 MW/s
- At t=3s, power demand increased from 37.5 MW to 75 MW at the same power ramp rate
- At t=5s, power demand decreased to 0 MW at the same power ramp.

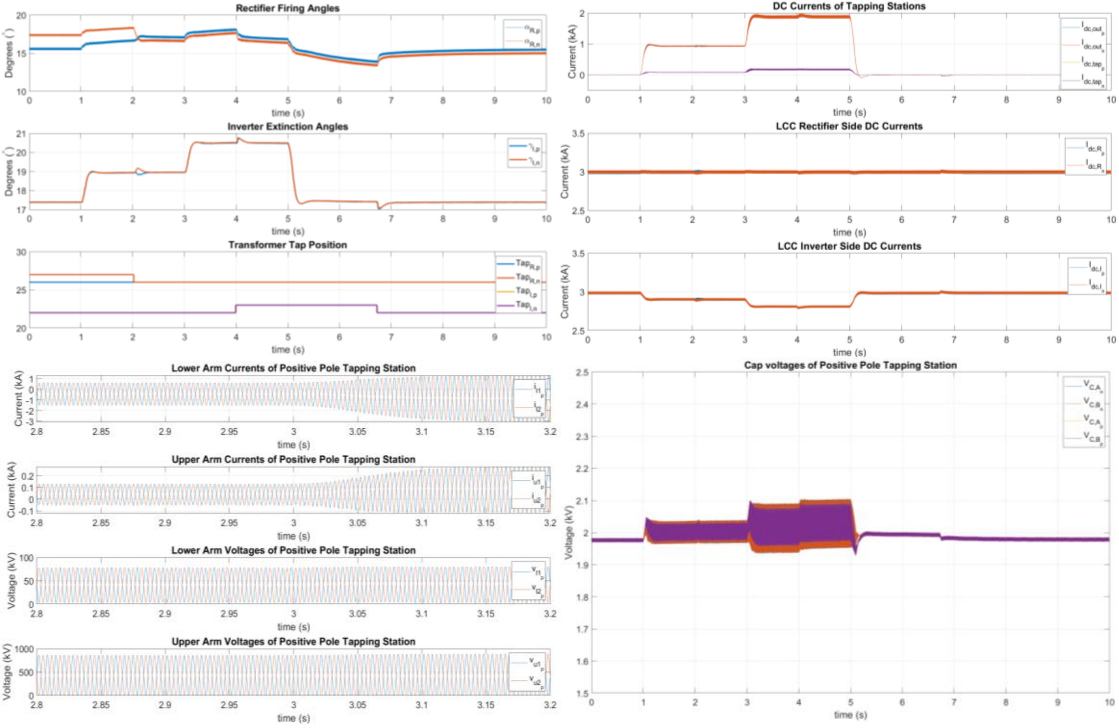


Figure 7: Symmetrical Power Tapping Results (P_{dcp}=P_{dcn})

In this scenario, the two tapping stations were operating identically, and the results are shown in Figure 7. Waveforms are overlaid where possible to emphasize the difference between LCC and tapping stations. There were minor differences in the firing angles of the rectifier stations due to the tap changer position on the transformer at the respective pole. The variation of the SM capacitor voltages change depending on the power tapping demand. As expected, the voltage ripples were highest when rated power demand was set. Rectifier side DC currents were maintained at 3 kA due to CCA being active. The inverter side DC currents are reduced by an amount equal to the tapping current at the corresponding pole's tapping station. The inverters continue to run constant extinction angle (CEA) control because the HVDC current being tapped is always less than the current margin.

3.3. Asymmetrical Power Tapping

During asymmetrical power tapping, $P_{dc,p}=2\times P_{dc,n}$. The power demand had three instances of change:

- At t=1s, power demand increased from 0 MW to 37.5 MW at a rate of 750 MW/s for $P_{dc,p}$ while $P_{dc,n}$ increased to 18.75 MW at the same power ramp rate.
- At t=3s, power demand increased from 37.5 MW to 75 MW for $P_{dc,p}$ while $P_{dc,n}$ increased to 37.5 MW at the same power ramp rate.
- At t=5s, power demand decreased to 0 MW at the same power ramp.

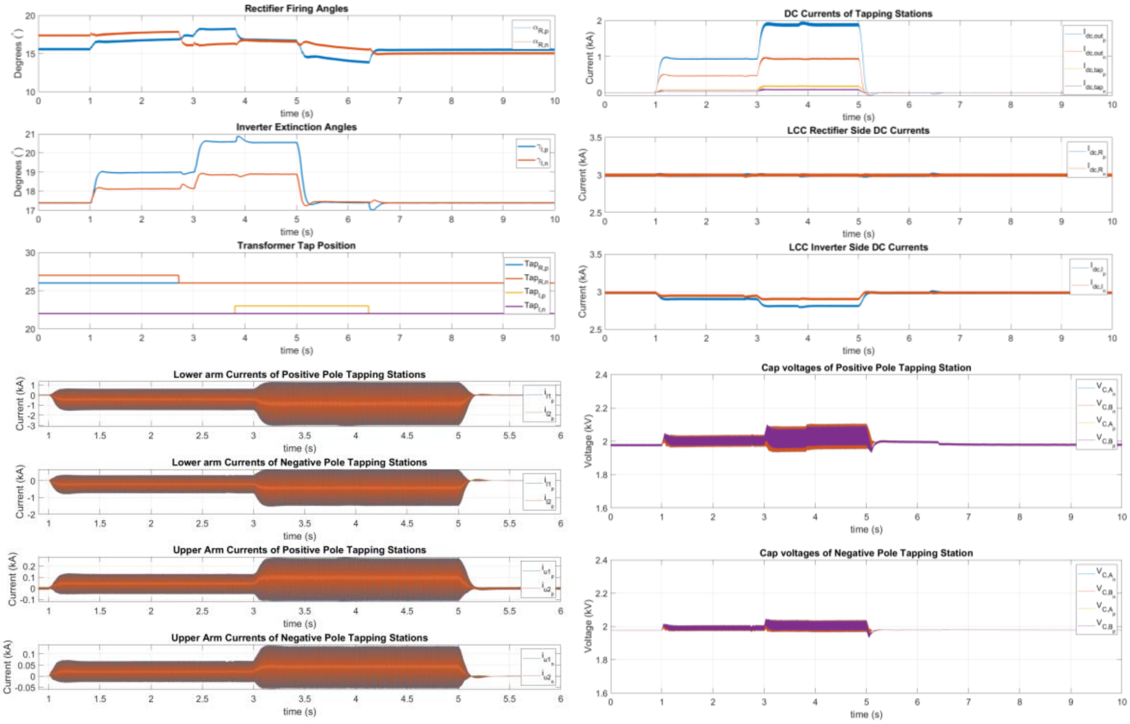


Figure 8: Asymmetrical Power Tapping

Asymmetrical tapping results are shown in Figure 8. The modes of operation for the LCC-HVDC bipole system remain unchanged from the symmetrical tapping scenario. That is, the LCC bipole was able to accommodate power tapping imbalance between poles without any change in operating mode (rectifiers stay in CCA and inverters stay in CEA). Note that the positive and negative pole LCC inverters see different DC currents, due to the fact different amounts of power are being tapped from each pole. However, both rectifiers always see 3 kA DC current due to CCA being active. This means that some (small) amount of DC current is being circulated on the neutral return path between the tapping stations and the inverters, through the ground electrode path.

4. Conclusion

In this work, a detailed hybrid LCC-VSC HVDC bipole system was developed in RSCAD that contains two DC tapping stations, one for each pole, realized via 500:40 kV DC-DC converters using MMC technology. These tapping stations were confirmed to operate independently up to their designed 75 MW rating, without detrimental impact to the backbone LCC-HVDC system. In the case of asymmetrical power tapping between poles, an interesting outcome is that part of the neutral return path between inverters and tapping stations is forced to carry some amount of DC current.

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