Two novel thyristor based HVDC topologies for independent control of active and reactive power

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***Abstract*—IGBT based VSC (Voltage Source Converter) HVDC is rapidly maturing as a technology, and offers some significant advantages compared to traditional thyristor based HVDC, such as independent control of active and reactive power. This independent control enables VSC HVDC to operate in very weak AC systems and fluctuant power transmission systems, however thyristor based HVDC technology still has a considerably higher DC current capability than VSC technology. Wind power development is booming globally, and large scale onshore wind power is under development in China, the Americas and India. Compared with AC transmission, HVDC technology can due to lower losses be attractive if the distance from generation to consumption is long. Onshore wind conditions require both very high DC current capability, and control flexibility due to weak AC systems with fluctuant power. Therefore, there is good reason to investigate new solutions to complement existing VSC and conventional HVDC technology. In this paper, an evaluation of two such novel thyristor based HVDC topologies for independent control of active and reactive power is presented. The first alternative, based on the AHBC (Adaptive Harmonic Blocking Compensator) [13], is a combination of a FC-TCR (Fixed Capacitor - Thyristor Controlled Reactor) and LCC (Line Commutated Converter) HVDC. Apart from independent control of active and reactive power, it offers great AC harmonic reduction. The second alternative, based on the SPVC (Series Pulsed Voltage Compensator) [14], is a controllable series capacitor that can dynamically modify the thyristor valve voltages. Controllable reactive power can hence be achieved. This topology also shows some AC harmonic reduction. The fundamentals of circuit operation, main circuit calculation, and time domain simulation results are shown and discussed. These two topologies are then compared with traditional LCC HVDC, advantages and disadvantages are shown.**

Keywords*— HVDC transmission; Thyristors; Insulated gate bipolar transistors; Power system control; Reactive power control; Wind energy integration

I. Introduction

The introduction of IGBT based VSC (Voltage Source Converter) HVDC [1], [2] brought with it significant advantages compared to the thyristor based classical HVDC [3], such as independent control of active and reactive power. This independent control enables VSC HVDC to operate in very weak AC systems and fluctuant power transmission systems [4]. The introduction of MMC (Modular Multilevel Converter) [5], made it relatively easy to scale VSC HVDC upwards in terms of DC voltage, however thyristor based HVDC technology still has a considerably higher DC current capability than VSC technology. Today's highest rated thyristor valves in commercial operation are rated at 5000A, with 6250A on the horizon [6].

Wind power development is booming globally, and large scale onshore wind power is under development in for instance China [7], the Americas [8]-[10] and India [11]. It is also perceivable that the abundant onshore wind resources in for instance Mongolia and Kazakhstan [12], could be utilized in the future by large capacity, long distance HVDC transmission. Onshore wind conditions require both very high DC current capability, and control flexibility due to weak AC systems with fluctuant power. Therefore, there is good reason to investigate new solutions to complement existing VSC and conventional HVDC technology. In this paper, an evaluation of two such novel thyristor based HVDC topologies for independent control of active and reactive power is presented.

In section II, a HVDC adaptation of the AHBC (Adaptive Harmonic Blocking Compensator) [13] system, is introduced and evaluated against a normal LCC HVDC converter. This novel topology is named AHBC-HVDC. Similarly in section III, a thyristor based equivalent circuit of the SPVC (Series Pulsed Voltage Compensator) [14], is introduced and evaluated. This novel topology is named SPVC-T. A typical ± 800 kV UHVDC system is used for all evaluation, and conclusions about the two novel thyristor based HVDC topologies are drawn in section IV. Appendix A lists the main circuit parameters used, and shows some selected time domain simulation of the AHBC-HVDC system. Appendix B lists the main circuit parameters used, and shows some selected time domain simulation of the SPVC-T system. PSCAD is used and rectifier quantities are shown for all time domain simulation.

II. The AHBC-HVDC system

In this section, a HVDC adaptation of the AHBC system [13] is introduced and evaluated, advantages and disadvantages are discussed, and the fundamentals of circuit operation and main circuit design are shown.

A. Brief description of the original AHBC system

A system overview is shown in Fig. 1. The upper left hand side is the three-phase AC network interface, while the upper right hand side is the three-phase non-linear load interface (such as a 6-pulse Graetz Bridge).

The AHBC system is designed as a highly multifunctional system that is capable of:

- Controllable reactive power. This is performed by the shunt connected FC-TCR (inside the green square), formed by the antiparallel thyristor pairs, capacitors C and inductors Lc.
- Balancing an unbalanced load. This is also performed by the shunt connected FC-TCR, but generates additional harmonics, especially 3rd. Due to this, a 3rd filter, formed by C3 and L3, is used.
- Filter higher order harmonic currents originating from a non-linear load (inside the blue square). This is achieved by choosing suitable values of the components. The filter formed by Cf and Lf are tuned to the fundamental AC network frequency (inside the purple square). For higher frequencies, harmonic current from the non-linear load will naturally pass through capacitor C instead, hence acting as a wide band harmonic filter.

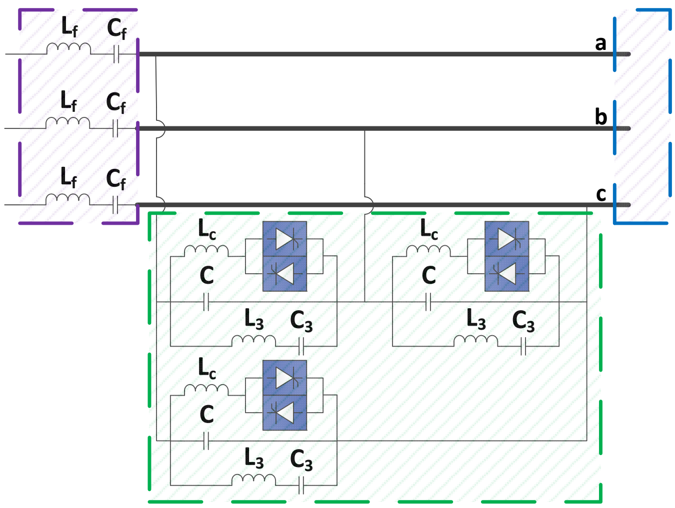

Fig. 1. Overview of the original AHBC system

The CSL is solely needed to slow down the current derivative during the normal commutation process of the 6-pulse Graetz Bridge. An illustration of the relevant commutation impedances is shown in Fig. 3. The 6-pulse Graetz Bridge is just commutating from valve 1 (phase a) to valve 3 (phase b). Valve 2 (phase c) is omitted for clarity. The reason why commutation is so much faster, is that the almost perfectly square wave shaped commutation current will see a much lower commutation impedance through the capacitor C1, compared to that of the parallel converter transformer inductance between phase a and b, labeled 2*LT. This is also true if the TCR fires, and connects inductance L1 in parallel with C1 and 2*LT, as shown in Fig. 3.

B. Introduction of the AHBC-HVDC system

A system overview is shown in Fig. 2. The key differences compared with the original AHBC system are the following:

- No balancing functionality is provided, hence a 3rd harmonic filter is not necessary in the FC-TCR
- The converter transformer inductance LT is enough to achieve a high degree of AC harmonic filtering
- A CSL (Commutation Speed Limiting) reactor is added (inside the red square)

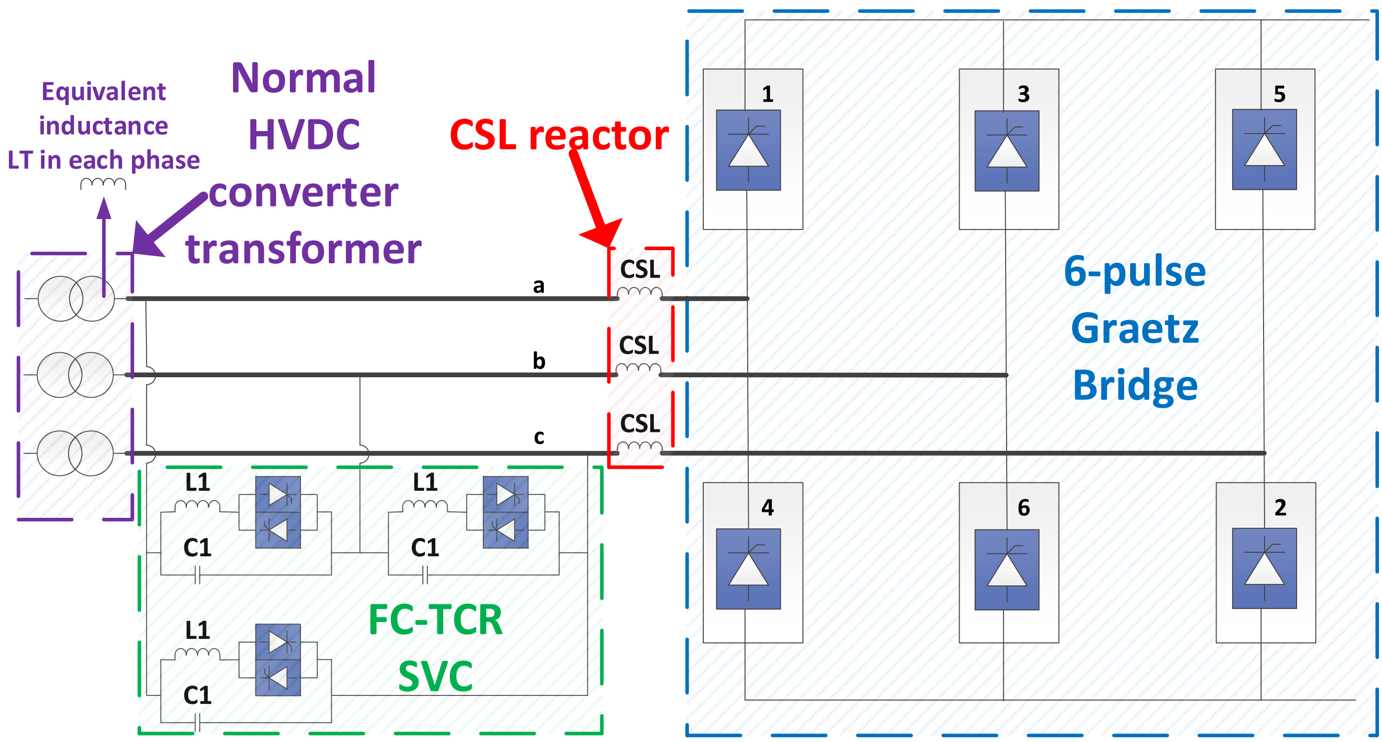

Fig. 2. Overview of the AHBC-HVDC system

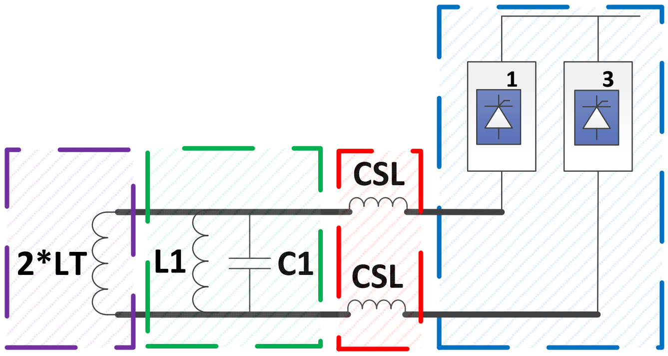

Fig. 3. Commutation impedances when the 6-pulse Graetz Bridge is commutating from valve 1 to valve 3, with the TCR fired

For HVDC application, phase controlled thyristors are preferable since a low switching frequency is used, hence the on-state losses can be minimized. These type of thyristors have a maximum allowable current derivative, which is typically in the range of 100-250 A/µs [15].

C. *Key advantages and disadvantages compared to a conventional LCC HVDC system*

The AHBC-HVDC system shows considerable advantages compared to a conventional LCC HVDC system:

- Drastic AC harmonic reduction since the shunt capacitor C1 acts as a wide band harmonic filter. This hence gives an extremely small AC yard, in a typical design only $11^{th}/13^{th}$ AC filters are needed. PLC-filters are not needed at all
- Very low AC overvoltage at load rejection due to fast TCR control
- The overlap duration is very short, which mainly affects two parts: Very low sensitivity towards commutation failures, and possibility to operate in weak AC systems due to a very flat UD/ID characteristic
- Decreased apparent power rating, and reduced harmonic losses of the converter transformers
- Lower 6-pulse Graetz Bridge valve damping circuit losses due to a smoother and more continuous valve voltage
- For the same level of current control margin, there will be lower 6-pulse Graetz Bridge peak voltage which means lower 6-pulse Graetz Bridge valve cost and losses

The AC harmonic reduction is of special interest. It can be explained in a very similar way as the fast commutation, by looking at the impedances in Fig. 3. The impedance of the inductance 2*LT increases linearly with frequency, while the impedance of the capacitor C1 decreases linearly with frequency. The harmonic current share of C1 will hence increase with a square of the frequency. In Table I, the relevant AC harmonic requirements for high AC voltage levels [16], and actual AC harmonics of a conventional LCC converter, the AHBC-HVDC converter, and finally the SPVC-T converter that will be introduced in section III are shown. All converters were simulated as conventional 12-pulse systems.

TABLE I. ALLOWED HARMONICS AND ACTUAL EMISSIONS, IN PERCENT

Harmonic	*IEEE-519 2014*	*LCC HVDC*	*AHBC-HVDC*	*SPVC-T*
11^{th}	0.50%	3.20%	0.94%	2.67%
13^{th}	0.50%	2.10%	0.51%	2.65%
23^{rd}	0.15%	0.94%	0.09%	0.82%
25^{th}	0.15%	0.77%	0.06%	0.88%
35^{th}	0.10%	0.37%	0.03%	0.23%
37^{th}	0.10%	0.34%	0.02%	0.31%
47^{th}	0.10%	0.13%	0.01%	0.02%
49^{th}	0.10%	0.12%	0.01%	0.03%
THD total	1.50%	4.10%	1.13%	4.03%

Although the AHBC-HVDC system shows considerable advantages compared to a conventional LCC HVDC system, there are also considerable disadvantages:

- Risk of low order harmonic resonance with the AC network. Seen from the AC network side of the transformer, a series resonance circuit is formed by the transformer inductance 2*LT and the capacitor C1
- Excessive reactive power generation at low HVDC power levels. This in turn gives an large TCR rating (typical value is ~0.5 p.u of the HVDC rating)
- A “fourth phase” hot spare capacitor C1 is most likely necessary for high availability and redundancy. A “fourth phase” means that if a single C1 capacitor trips, a spare capacitor C1 can quickly be connected to any of the three phases, similar to how the AC filters are implemented in the Garabi BtB HVDC project [17]
- A lot of equipment that needs to be insulated from the 6-pulse Graetz Bridge DC voltage offset and also the C1 capacitor voltage
- Increased DC harmonics due to the short overlap

D. *Fundamental circuit operation, and main circuit design*

At AC energization of the complete system, the TCR should initially be fired, in order to not inject excessive reactive power to the AC grid. Apart from this, the FC-TCR and the HVDC converter does not need any particular coordination, nor is there a need for any special control. For instance the FC-TCR can operate in conventional AC voltage control mode, regardless of operational status of the HVDC.

The key issue in main circuit design can be summarized as: Seen from the 6-pulse Graetz Bridge, a parallel resonance circuit is formed by the transformer inductance LT, and the capacitor C1. If the parallel resonance comes too close to that of the naturally emitted AC current harmonics, starting at the 5^{th} harmonic, very large over-voltages will occur over the 6-pulse Graetz Bridge. Due to this, the parallel resonance must be designed at a value lower than the 5^{th} harmonic.

$$P_{res} = \frac{1}{2\pi\sqrt{(LT * C1)}} < 5 * F_{nom} \quad (1)$$

Pres=The parallel resonance, in Hz
LT=The transformer inductance (single phase), in H
C1=The capacitor capacitance, in F
Fnom=The nominal AC frequency, in Hz

In order to determine C1 with a given transformer inductance LT, below equation is used.

$$C1 = \frac{\left(\frac{1}{2\pi * F_{nom}} \right)^2}{LT} \quad (2)$$

The resonance restriction has a major impact on the overall main circuit design. The converter transformer inductance must be chosen fairly high, in order to get a fairly low capacitance. Even with a fairly low capacitance, there will be considerable reactive power generation from the capacitor.

$$Q_{C1} = UT^2 * 2\pi * F_{nom} * C1 \quad (3)$$

QC1=The total reactive power generated, in MVAr
UT=The transformer phase-to-phase RMS voltage on the HVDC winding side, in kV

In order to let the TCR consume reactive power, especially when the HVDC converter does not operate, the inductance L1 must be chosen to a fairly high value.

$$L1 = \frac{UT^2}{Q_{C1} * L_{fact} * 2\pi * F_{nom}} \quad (4)$$

L_{fact}=A multiplication factor, typical value of 1.1

In above equations, a star connection of the FC-TCR is assumed. If a delta connection is used like in Fig. 2, the capacitance of C1 from (2) should be divided by 3, and correspondingly the inductance value of L1 from (4) should be multiplied by 3.

III. The SPVC-T System

In this section, a thyristor adaptation of the SPVC system is introduced and evaluated, advantages and disadvantages are discussed, and the fundamentals of circuit operation and main circuit design are shown.

A. Brief description of the original SPVC system

A system overview is shown in Fig. 4. The SPVC system can be seen as a variable series capacitor, placed between the converter transformer and the 6-pulse Graetz Bridge. As a matter of fact, it is a full bridge converter. Variable reactive power control is achieved by selective insertion and removal of the capacitor Cfb, while always keeping a continuous current flowing through the SPVC. The key difference compared to a CCC HVDC system [18] is that a very small capacitance can be used, since a capacitor bypass is always possible. Another difference is that the capacitor is never inserted when a phase is being commutated out. This prolongs the overlap, which gives a harmonic reduction.

B. Brief description of the SPVC-T system

A system overview is shown in Fig. 5. SPVC-T can also be seen as a variable series capacitor. The key differences compared with the original SPVC system are the following:

- Since the switching frequency of the SPVC is very low, thyristors can be used instead of IGBTs
- Thyristors have lower cost, losses, and most importantly for intended large-scale onshore wind application, a much higher current capacity
- The capacitor CS must be of a conventional AC type, and not the advantageous DC type as in the original system

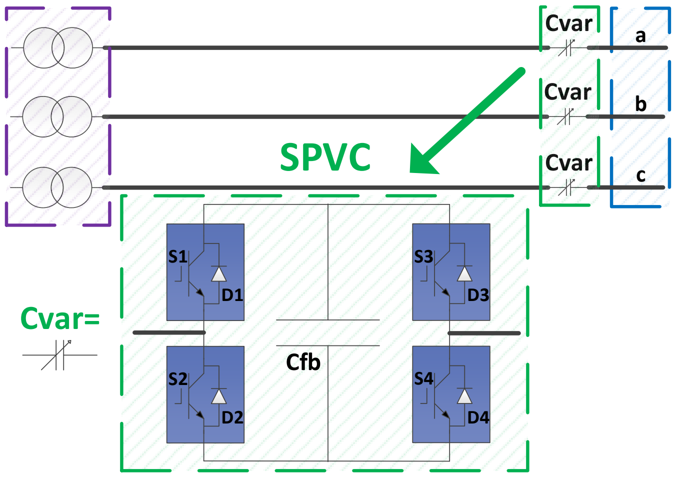

Fig. 4. Overview of the original SPVC system

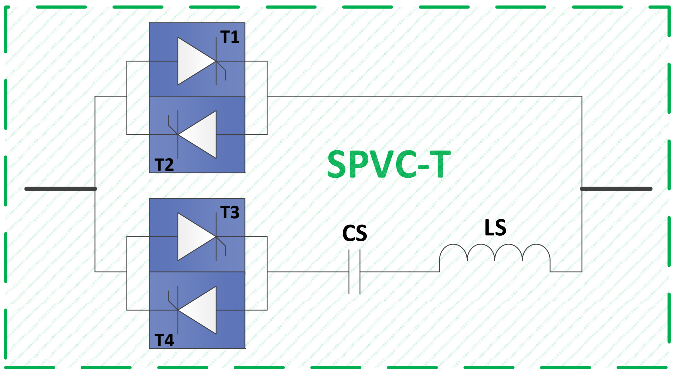

Fig. 5. Overview of the SPVC-T system

C. Key advantages and disadvantages compared to a conventional LCC HVDC system

The SPVC-T system shows some advantages compared to a conventional LCC HVDC system:

- Very high reactive power controllability
- AC and DC harmonics decrease slightly
- A much smaller AC yard since only harmonic filters are needed
- Much lower AC overvoltage at load rejection, due to less shunt connected capacitance

The SPVC-T system also shows some disadvantages compared to a conventional LCC HVDC system:

- A lot of equipment that needs to be insulated from the 6-pulse Graetz Bridge DC voltage offset and also the CS capacitor voltage
- Increased losses since more thyristors are always in series with the DC current
- At a high degree of series compensation, the rectifier will easily loose current control to the inverter, due to a low control margin

D. Fundamental circuit operation, and main circuit design

Fig. 6 shows steady state operation of the original SPVC [14], and it is divided into 12 discrete instants. The red curve is the voltage across the SPVC; the blue curve is the current through the SPVC; the green curve is the AC grid voltage and the **black** lines are the 12 instants. The definition of the 12 instants are given below:

1) The 6-pulse Graetz Bridge commutates out from negative period
2) The SPVC inserts an assisting voltage polarity, so that the 6-pulse Graetz Bridge can be fired earlier. This is the reactive power control
3) The 6-pulse Graetz Bridge fires in the positive period
4) The capacitor changes polarity, and bypass mode is entered
5) The capacitor is charged to a controlled voltage
6) Bypass mode is entered
7) The 6-pulse Graetz Bridge commutates out from positive period
8) The SPVC inserts an assisting voltage polarity, so that the 6-pulse Graetz Bridge can be fired earlier. This is the reactive power control
9) The 6-pulse Graetz Bridge fires in the negative period
10) The capacitor changes polarity, and bypass mode is entered
11) The capacitor is charged to a controlled voltage
12) Bypass mode is entered again

Since the SPVC-T uses thyristors, it is not as flexible as the original SPVC. However, it can replicate the same fundamental behavior with some smaller changes. The changes are:

- The bypass from instant 4 to 5, and from 10 to 11, can be performed, but would leave the CS capacitor uncharged. The capacitor charge is the key to controlling the commutation at instant 8 and 2.
- The thyristors hence needs to be fired continuously from instant 2 to 6, and from 8 to 12 respectively.

In order to clarify the actual operation of the SPVC-T, Table II shows when each thyristor is fired, and also which thyristor(s) that are conducting current until the next instant is reached. In addition, Fig. 7 shows the actual circuit at instant 6, with the related charge polarity of the CS capacitor. At instant 6, T1 is fired when T3 is already conducting current. Due to the voltage polarity of the capacitor CS, the current will naturally commutate to T1.

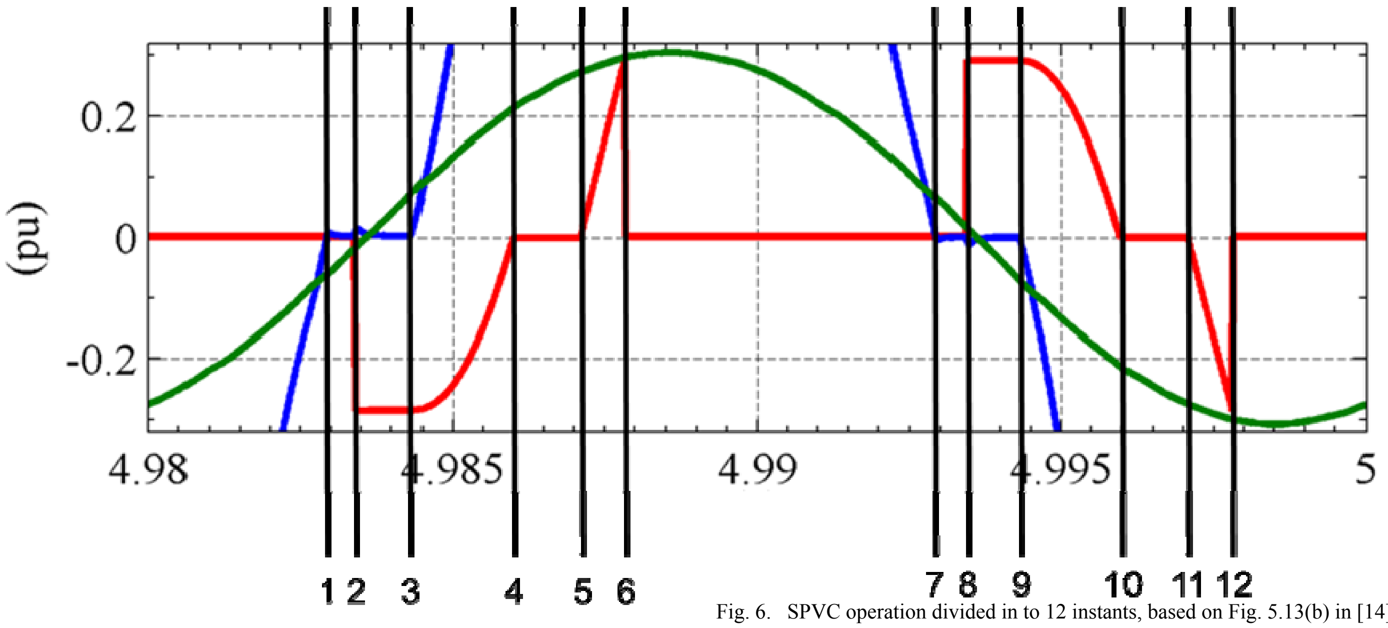

Fig. 6. SPVC operation divided in to 12 instants, based on Fig. 5.13(b) in [14]

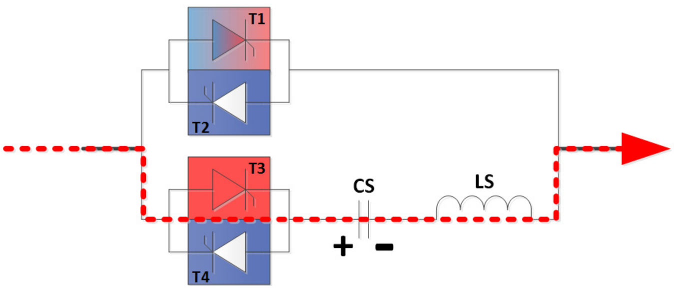

Fig. 7. The SPVC-T system, at instant 6

TABLE II. SWITHCING AND CONDUCTION OF THE SPVC-T

Instant	*Firing thyristor*	*Conducting thyristor(s)*
1	x	T2
2	T3	T3
3	x	T3
4	x	T3
5	x	T3
6	T1	T3+T1
7	x	T1
8	T4	T4
9	x	T4
10	x	T4
11	x	T4
12	T2	T4+T2

For main circuit design, the key issue is the voltage across the CS capacitor. In order to have a high amount of reactive power compensation, a large amount of charge needs to be stored in the capacitor. This will lead to a high voltage level. The thyristors (T1 to T4) needs to be able to withstand this voltage.

In a similar manner to the CSL reactor in the AHBC-HVDC system, the function of the LS reactor is to provide a safe thyristor current derivative at commutation of the SPVC-T.

IV. CONCLUSION

In this paper, two novel thyristor based HVDC topologies for independent control of active and reactive power were presented, namely AHBC-HVDC and SPVC-T.

The AHBC-HVDC system shows considerable advantages compared to a conventional LCC HVDC system. However, the limitations implied by the 5th harmonic resonance condition, gives excessive reactive power generation at low HVDC power levels. This also makes the system susceptible to low order harmonic AC network resonances.

The SPVC-T system shows some advantages and disadvantages compared to a conventional LCC HVDC system. If tuned AC filters are used, the physical area needed by the complete SPVC-T system can be made relatively small. However, the additional cost and loss of the SPVC-T thyristors must also be taken into consideration.

APPENDIX A, DETAILED MAIN CIRCUIT PARAMETERS AND SELECTED TIME DOMAIN SIMULATION PLOTS OF AHBC-HVDC

Simulation has been performed with proposed AHBC-HVDC topology by using the main circuit parameters listed in Table III and IV. Fig. 8 - Fig. 10 shows steady state simulation of the system, and when applicable the same quantities are compared to LCC HVDC. In Fig. 11, a critical fault case for the 6-pulse Graetz Bridge thyristors is shown, namely valve short circuit. All simulations are from rectifier operation, operating at nominal DC voltage and DC current.

TABLE III. COMMON SYSTEM DATA FOR AHBC-HVDC, LCC AND SPVC-T

Name	*Value*	*Unit*
Nominal DC voltage	±800	kV
Nominal DC current	4.375	kA
Number of 6-pulse groups/pole	4	-
Nominal AC voltage level	750	kV
Nominal AC voltage frequency	50	Hz
Nominal transformer three-phase rating	1060.2	MVA
Nominal transformer HVDC winding voltage	171.4	kV
Nominal transformer leakage reactance	18.0	%

TABLE IV. AHBC-HVDC SPECIFIC SYSTEM DATA

Name	*Value*	*Unit*
CSL reactance	0.002	H
C1 capacitance (delta connected)	19.543	μF
L1 reactance (delta connected)	0.4715	H

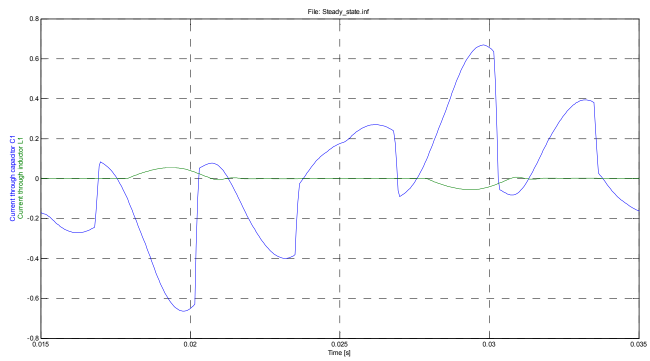

Fig. 8. Current stress of the shunt connected FC-TCR. Legend: Blue=Current through C1. Green=Current through L1. All in p.u

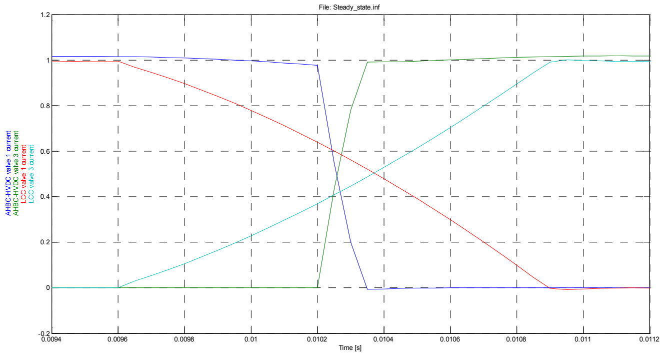

Fig. 9. Commutation of the 6-pulse Graetz Bridge, and related overlap. Legend: Blue and Green=AHBC-HVDC commutation currents. Red and Magenta=LCC commutation currents. All in p.u

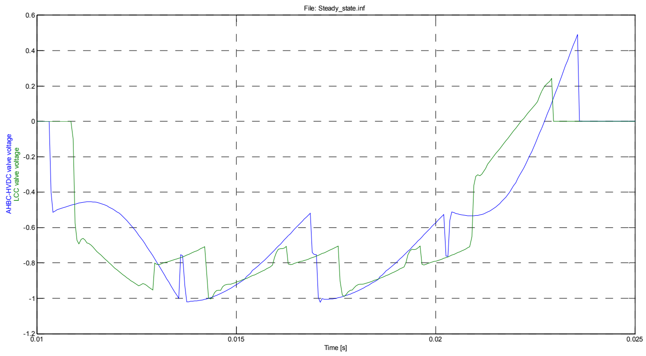

Fig. 10. Voltage stress of 6-pulse Graetz Bridges. Legend: Blue=AHBC-HVDC 6-pulse Graetz Bridge voltage. Green=LCC 6-pulse Graetz Bridge voltage. All in p.u

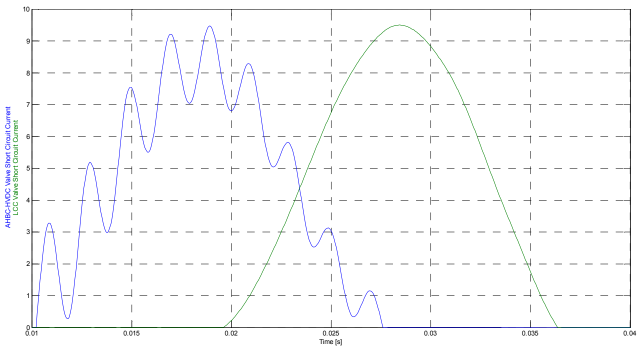

Fig. 11. Current stress of 6-pulse Graetz Bridges at valve short circuit Legend: Blue=AHBC-HVDC 6-pulse Graetz Bridge current. Green=LCC 6-pulse Graetz Bridge current. All in p.u

APPENDIX B, DETAILED MAIN CIRCUIT PARAMETERS AND SELECTED TIME DOMAIN SIMULATION PLOTS OF SPVC-T

Simulation has been performed with proposed SPVC-T topology by using the main circuit parameters listed in Table III and V. Fig. 12 - Fig. 14 shows steady state simulation of the system, and when applicable the same quantities are compared to LCC HVDC.

TABLE V. AHBC-HVDC SPECIFIC SYSTEM DATA

Name	***Value***	***Unit***
CS capacitance	45	µF
LS reactance	0.003	H

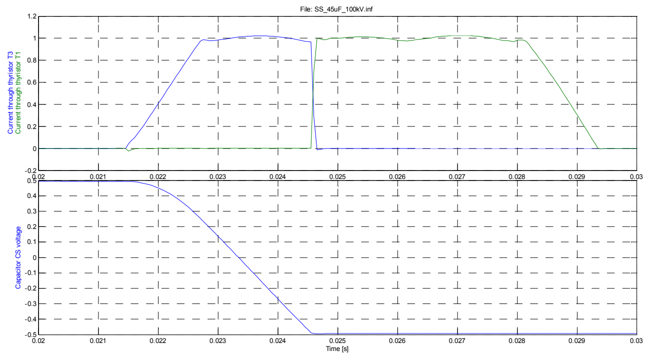

Fig. 12. . Operation of the SPVC-T, and polarity change of the CS capacitor. Legend: Graph 1; Blue=Current through thyristor T3. Green=Current through thyristor T1. Graph 2; Blue=Voltage across capacitor CS. All in p.u

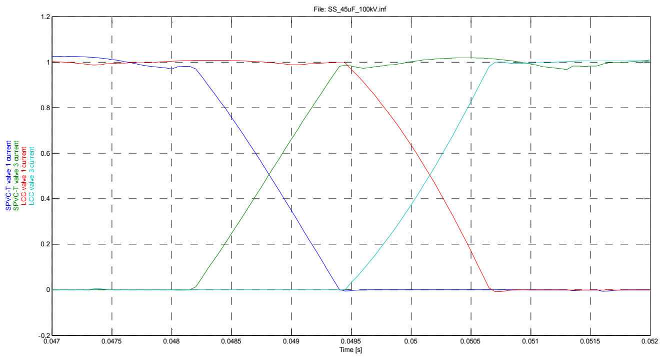

Fig. 13. Commutation of the 6-pulse Graetz Bridge, and related overlap. Legend: Blue and Green=SPVC-T commutation currents. Red and Magenta=LCC commutation currents. All in p.u

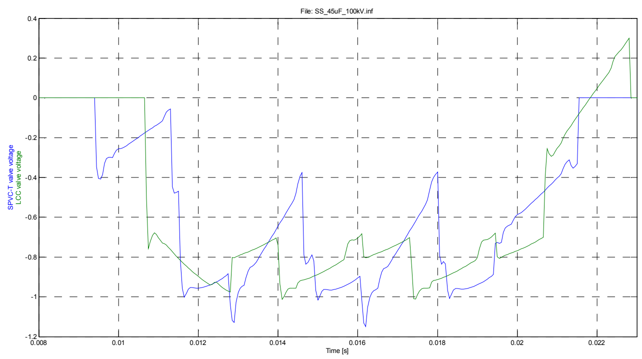

Fig. 14. Voltage stress of 6-pulse Graetz Bridges. Legend: Blue=SPVC-T 6-pulse Graetz Bridge voltage. Green=LCC 6-pulse Graetz Bridge voltage. All in p.u

In a similar manner to the CSL reactor in the AHBC-HVDC system, the function of the LS reactor is to provide a safe thyristor current derivative at commutation of the SPVC-T.

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