ANALYSIS OF TRANSIENT STABILITY IN CSCC - HVDC SYSTEMS CONNECTED BETWEEN TWO WEAK ELECTRICAL SYSTEMS

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***Abstract* – This work presents analysis and simulation of the transient state behavior of a Controlled Series Capacitor Commutated Converter (CSCC) in High Voltage Direct Current (HVDC) system, compared to Capacitor Commutated Converter (CCC)-HVDC and conventional HVDC systems for different operation conditions. The objective is to shown the viability of modern CSCC-HVDC systems to interconnect two weak AC systems. The systems were implemented in Alternative Transient Program, based in CIGRÉ HVDC Benchmark model, adding the controlled series capacitor compensator. Additionally, it shown the comparison of reactive power level compensated and THD percent between all models.**

***Keywords* – CCC, CSCC, HVDC, Transient State, Weak AC systems.**

I. INTRODUCTION

Up until now, the HVDC Systems have been improved continuously [1]. However, the use of the conventional system is still used in its different aplications. For example, the so called Back to Back Systems, is used as a solution to interconnect two asynchronous systems, or to transport large amount of power for hundreds of kilometers. However, the conventional HVDC systems connected or interconnecting to weak electrical systems whose SCR (Short Circuit Ratio) is smaller to 2.5 are susceptible to different type of disturbances whose effects could be: the collapse of voltage, commutation failures, interactions with turbogenerators near to the converters systems, and so on [2], [3]. In order to mitigate these problems, different strategies were proposed to control the thyristors firing angles [4], being such strategies deficient for extreme cases, such as single-phase failures in the inverter side of the HVDC system. On the other hand, for the problem of deficiency of reactive power, were proposed CCC-HVDC systems [5], improving the operation during the failure instants, however, in some conditions of operation presents risks of generating high overcurrent and overvoltage. New systems CSCC-HVDC are proposed as a new alternative with the controlled serial compensation. The main advantage of this approach is that it increases the transitory stability of the interconnected weak electrical systems, overcomes the deficiencies presented in conventional systems and the CCC-HVDC, decreasing the consumption of reactive power, as it is possible to be appreciated in the obtained results from previous transitory test.

II. HVDC SYSTEM MODELING

HVDC Model used in this work, is the first model of CIGRE HVDC Benchmark [6]. The control method used is of 12 pulses, Vd=500 kV, Pd=1000 MW. The model and the controllers are not available in the ATP-Draw 4.2-2006 (program used in this work), the models have been implemented in the program and compared with the models available in PSCAD-EMTDC and the MatLab.

The system in study has the following characteristics:

Rectifier: SCR=2.5<-85º ; ESCR=1.9<-82°

Inverter: SCR = 2.0<-75º; ESCR = 1.9<-70°

The power system is composed of: AC side, DC side, and conversion units.

A. AC side:

1) Equivalent system: It can adopt different configurations: R-L, R-R-L, L-L-R. The value is calculated from (1).

$$Z_s = \frac{V_l^2}{P_d * SCR} \qquad (1)$$

Where:

Z_s - Source impedance

V_l, - Voltage of AC side,

Pd - Nominal power of HVDC system.

SCR - Short Circuit Ratio

2) The compensation system: The reactive power compensation required is around 50% of MW to transfer in conventional systems:

$$ESCR = SCR - \frac{Q_c}{P_d} \qquad (2)$$

Where:

Qc - Total Reactive Power.

ESCR - Efective Short Circuit Ratio

The MVARs are provided by the AC system, from the compensation system and the filters.

3) Converter Transformer: This is normally determined with a power of 1.2 pu of total MW power to transfer by HVDC system, with Lpu=0.15-0.18 pu, in the present case was chosen 0.18 pu. The configuration of the transformers can be: Single-phase with three windings, Single-phase with two windings, connected in delta-star with neutral connected to ground in the AC side.

4) AC Filters: the filters absorb the harmonics produced by the converter (6-12n+/-1), and injects reactive power according to its capacity, the design is obtained from (3), and the filter is from (4) and (5).

$$C = \frac{MVar}{V_{ph}^{2} * \omega_f} \quad (3)$$

$$L = \frac{1}{\omega_r^{2} * C} \quad (4)$$

$$R = \frac{\omega_r * L}{Q} \quad (5)$$

Where:

ω_r - Undesired harmonic frequency

ω_f - Fundamental frequency

Q - Quality factor, calculated using (6):

$$Q = \frac{1}{R} * \left[\frac{V_{ph}^{2}\omega_f}{MVAR * \omega_r} \right] \quad (6)$$

In (6), the value of R can be assumed, so that it allows obtaining suitable bandwidth and quality factor.

B. DC Side

The equations of system HVDC are given by 14 equations and 18 unknown variables [7]. They define the behavior of the DC system and from them is designed the control system:

1) Rectifier side

$$Id = (\cos(\alpha) - \cos(\alpha + \mu)) \frac{Vl_{rms}}{\sqrt{2}\,Xc} \quad (7)$$

$$Vd = \frac{3\sqrt{2}}{\pi} Vl_{rms} \cos(\alpha) - \frac{3}{\pi} XcId \quad (8)$$

$$\cos(\phi) \approx \frac{\cos(\alpha) + \cos(\alpha + \mu)}{2} \quad (9)$$

$$I \approx \frac{\sqrt{6}}{\pi} Id \quad (10)$$

$$\cos(\phi) \approx \cos(\alpha) - \frac{XcId}{\sqrt{2}Vl_{rms}} \quad (11)$$

2) Inverter side

$$Id = (\cos(\gamma) - \cos(\gamma + \mu)) \frac{Vl_{rms}}{\sqrt{2}\,Xc} \quad (12)$$

$$Vd = \frac{3\sqrt{2}}{\pi} Vl_{rms} \cos(\alpha) - \frac{3}{\pi} XcId \quad (13)$$

$$\cos(\phi) \approx \frac{\cos(\alpha) + \cos(\alpha + \mu)}{2} = -\frac{\cos(\gamma) + \cos(\gamma + \mu)}{2} \quad (14)$$

$$I \approx \frac{\sqrt{6}}{\pi} Id \quad (15)$$

$$\cos(\phi) \approx \cos(\alpha) - \frac{XcId}{\sqrt{2}Vl_{rms}} \quad (16)$$

Where:

Is -Current rms

Vlrms -Voltage of system AC side.

Xc - Commutation Reactance.

α, γ, μ -Firing angle, extinction angle, overlap angle.

Id, Vd -DC current and voltage.

$\cos(\phi)$ - Power Factor

3) Converter Model

It is represented by the three-phase Graetz model, where each one of the thyristors is protected by a parallel RC circuit Snubber which is given in Fig. 1, and designed using (17)

$$Rs > \frac{Ts}{Cs}, \quad Cs < \frac{P_{dph}}{1000 * 2\,pif * V_{l-l(rms)}} \quad (17)$$

The circuit, shown in Fig. 1, limits the di/dt and dv/di, RC snubber can be used for other objectives like avoiding the numerical oscillations [8], protecting the thyristors from quick changes of currents and from thermal damages.

C. HVDC Control System.

The control system acts on thyristors in the rectifier and inverter, based on the values of current and voltage, in AC and DC side of the system.

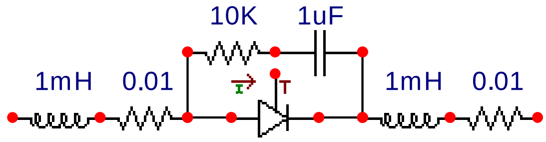


Fig. 1. Snubber Circuit

1) Firing angle control unit.

The thyristors are generally controlled with the firing angle through gate signals. For higher control precision are used the PLL control (Phase Locked Loop) [9], and VCO (Voltage Controlled Oscillator) [7], as shown in Fig. 2. The error of the signal is generated by the PI controller, from a value of reference in the VCO. The control system of the rectifier consists of a controlling the current of the rectifier, through the unit VDCOL (Voltage Dependent Current Order Limit) [7]

2) Current controller of the rectifier.

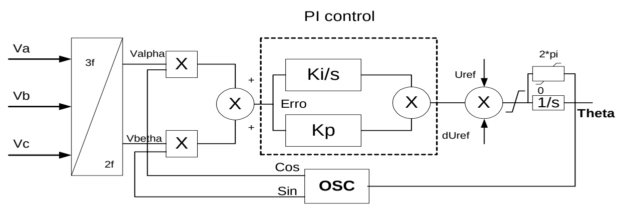


Fig. 2. Controller based in PLL and VCO

The simplified diagram of control is shown in Fig. 3.

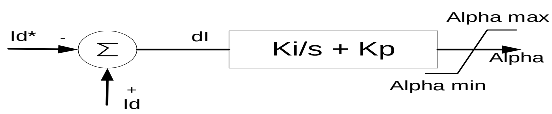


Fig. 3. DC current simplified controller.

The behavior of the controller of DC current, is based on (7) and (8) and it is possible to observe that, for an increase of DC current in the rectifier, *dI* is greater than 0, which increases *Alpha* (firing angle), and according to (7), Vd, increases. The control system of the inverter consists of both, the current controller and gamma controller (firing angle in the inverter) in parallel, the control system is shown in Fig. 3 and 4, from [7].

Fig. 4. Simplified controller of Extinction Angle.

D. Commutation failure

The commutation failure is very common in conventional systems that operate with converters based on thyristor, interconnected to weak AC systems, with SCR below 2.5, as is shown in Fig. 5. Due to the occurrence of single-phase failure in the inverter side, the thyristors 1 and 3 do not commutates the current, and thyristor 1 stays in state of conduction, this causes the considerable increase of the current in thyristor 1 and consequently DC current is reduced and the gamma angle increases.

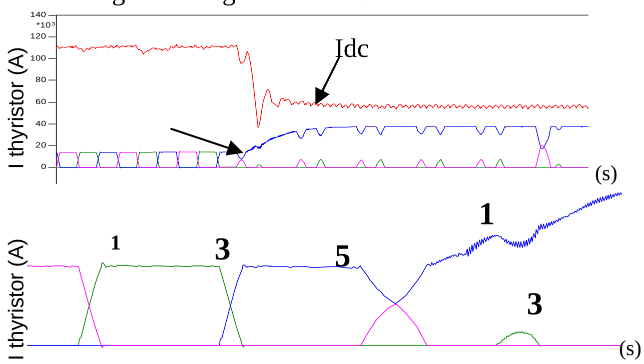


Fig. 5. Commutation failure in Inverter side.

E. CCC and CSCC (Capacitor Commutated Converter & Controlled Series Capacitor Converter).

CCC and CSCC are modern systems, which solved different problems in electrical systems, such as: Interconnection of weak systems, among others. The compensation of reactive power through the serial capacitors, improves the performance of the rectifier-inverter, extending the: stability region in electrical system, the power transference limit, the rank of variation of the ignition angle in thyristors; improves the performance in transitory state, the quality of energy during failures, the characteristic curve Id-Vd, decreases compensation level of reactive power and avoids commutation failures. Between systems CCC and CSCC, the main difference is in the control of possible subsynchronous resonances SSR [10], and subsynchronous torsional oscillations SSTI [3], these are avoided with the CSCC-HVDC. To calculate the value of the capacitor in the CSCC can be considered between 16 and 20% of the total reactance (transformer and the equivalent of the electrical system of the inverter side), the reactive power is between 20 to 30% of the required reactive power in conventional system, based in (19). To calculate the equivalent reactance of the CSCC based on the firing angle (antiparallel disposition) is used (18), all HVDC configurations are shown in Fig. 6.

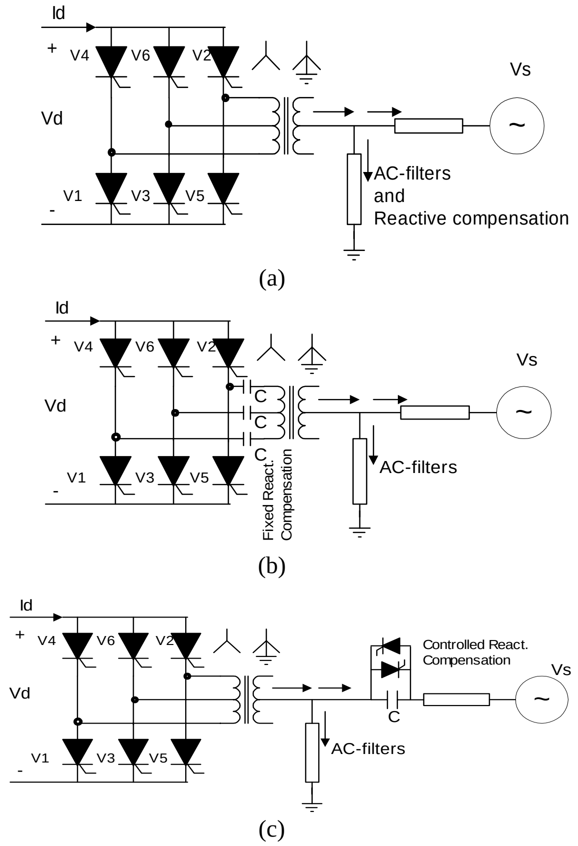


Fig. 6. (a) Conventional HVDC, (b) CCC-HVDC, (c) CSCC-HVDC.

$$Xe = -Xc\left[1 - \frac{k_x^{\,2}(\sigma + sen\sigma)}{(k_x^{\,2}-1)\pi} + \frac{4k_x^{\,2}\cos(\sigma/2)}{(k_x^{\,2}-1)^2\pi}\left(k_x \tan\frac{k_x\sigma}{2} - \tan\frac{\sigma}{2}\right)\right] \quad (18)$$

Where:

$\sigma = 2(\pi - \alpha)$,

$k_x = \sqrt{Xc/Xl} = \sqrt{rx}$

Xc - Equivalent capacitor reactance

Xe - Equivalent reactance

For the following values of HVDC system:

R	XL
5,6549	33,9

, considering the 20% result:

L	C
2,16	469,5

, for Xc/Xl=10 ratio, which results the reactives to compensate of 74,38 MVAr, from (19), [7]

$$MVAr = 3Xc * Il^2 \quad (19)$$

With the given values , the resonance angle is 152° therefore, the firing angle varies between 154 to 180° and in normal conditions it operates in 168°. For CCC system, the series capacitor is calculated using (20), from [7].

$$\frac{\partial \alpha_{\max}}{\partial CF} = 10\ [\deg/\ \ 100\ \%] \quad (20)$$

Where:

CF - Compensation factor, which is defined as:

$$CF = \frac{Xc}{Xt} \quad (21)$$

Where:

Xc -Reactance of series capacitor per phase.

Xt: -Reactance of the transformer.

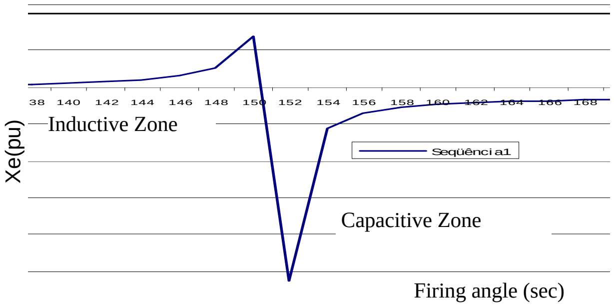


Fig. 7. Representation of the equivalent reactance based on the firing angle.

The serial compensation level are based in (18), from [11]. Normally in CCC systems, the total compensation level in reactive power is 3(4BP+HP+ Serial Capacitor), it represents a maximum of 25% of total active power to transfer by the HVDC system. This corresponds to a variation of the CF between 1 and 4. The effect of the CCC in $\alpha - and - \gamma$, is shown in [8] and graphically is shown in Fig. 7.

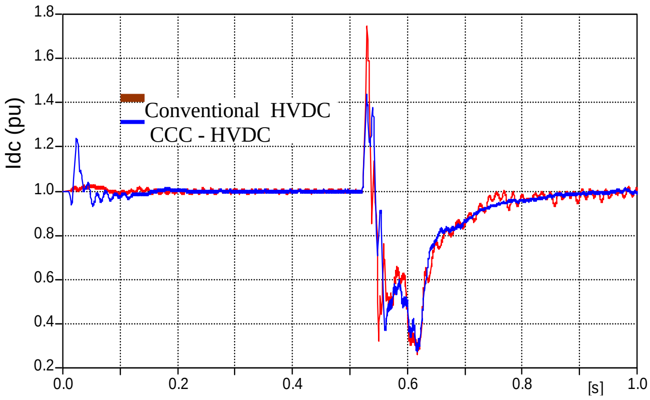
III. SIMULATIONS RESULTS

The modeled system is based on the CIGRE HVDC Benchmark, shown in [6] and [12]. All control systems were modeled using the MODELS programming language proper of ATP program [13]. The system is of 500 kV, 1000 MW, 2 kA dc. The representation of the system is in the ATP-Draw [14].

A. Cases of studies

Three-phase failures were performed in the inverter side considering different voltage drop levels (Case 1= 0%, Case 2 = 50%, Case 3 = 75% and Case 4 = 25%).

Fig. 8 - 11 shown the Idc (pu), Vdc (kV), and Ivalve (A), for all cases.



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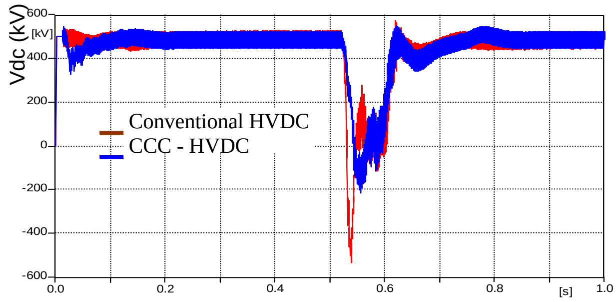

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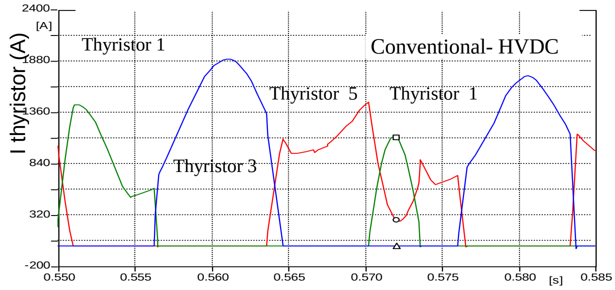
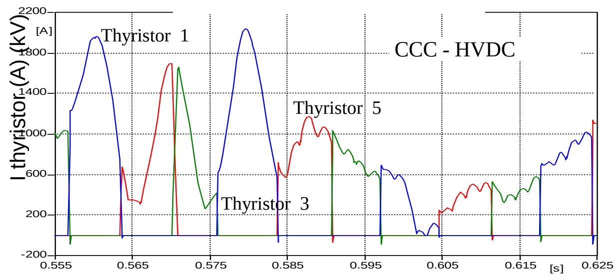
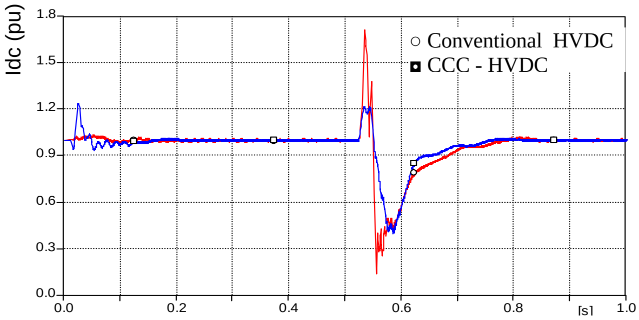


(c)

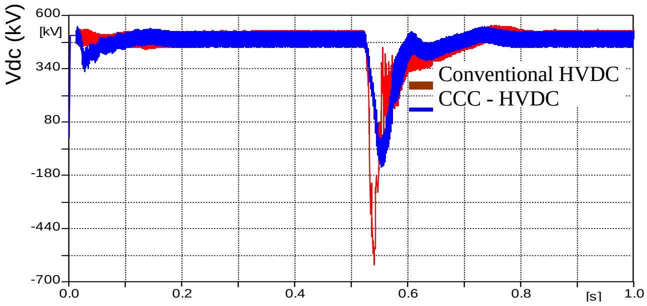


(d)

Fig. 8. (a) Idc (pu), (b) Vdc (kV), conventional HVDC Compared with CCC-HVDC, (c) I thyristor (A), conventional HVDC, (d) I thyristor (A) CCC-HVDC. All for Case 1.



(a)



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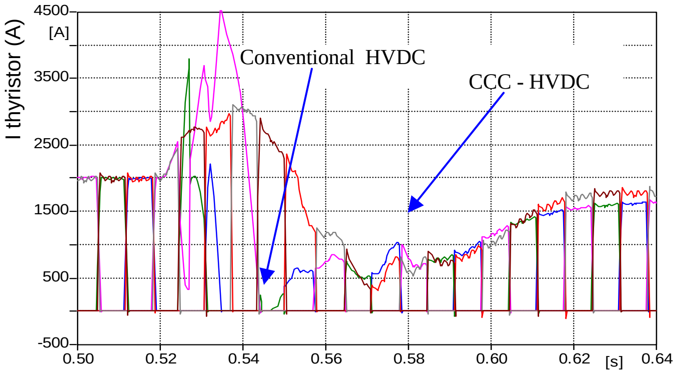
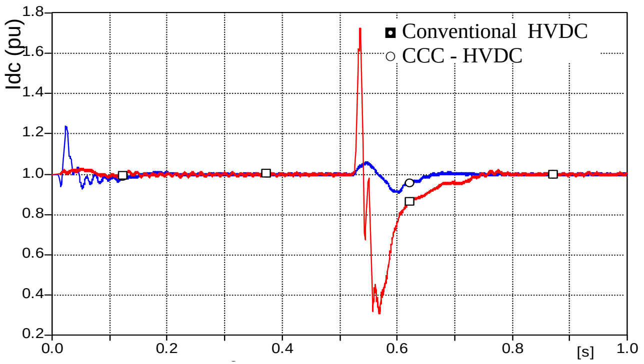
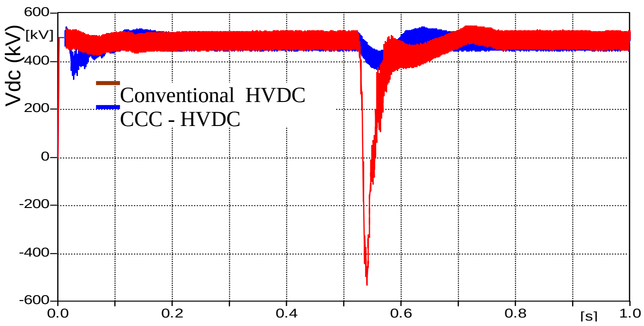


(c)

Fig. 9. (a) Idc (pu), (b) Vdc (kV), (c) I thyristor (A), Conventional HVDC compared with CCC-HVDC. All for Case 2.



(a)



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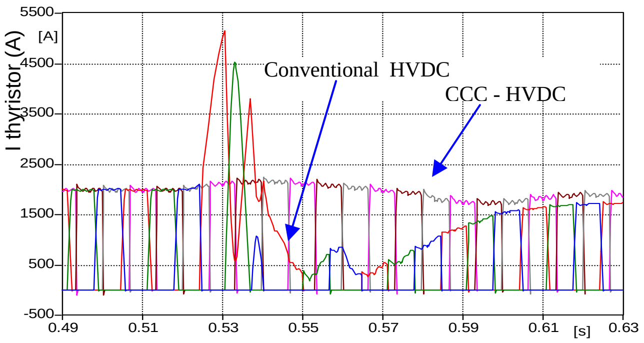
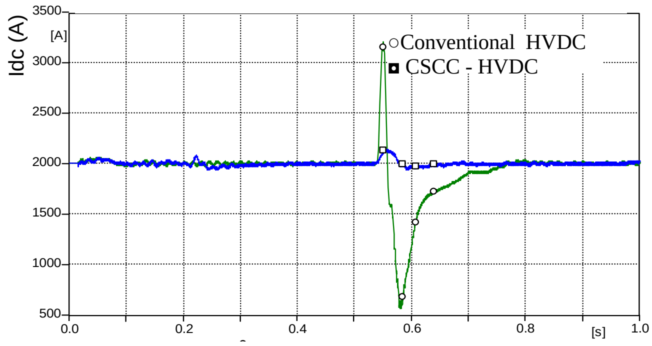
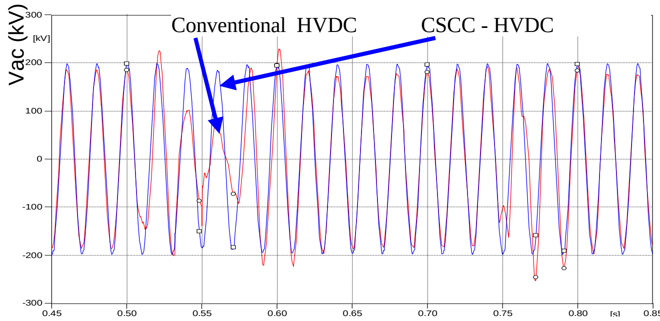


(c)

Fig. 10. (a) Idc (pu), (b) Vdc (kV), (c) I thyristor (A) Conventional HVDC compared wiith CCC-HVDC. All for Case 3.



(a)



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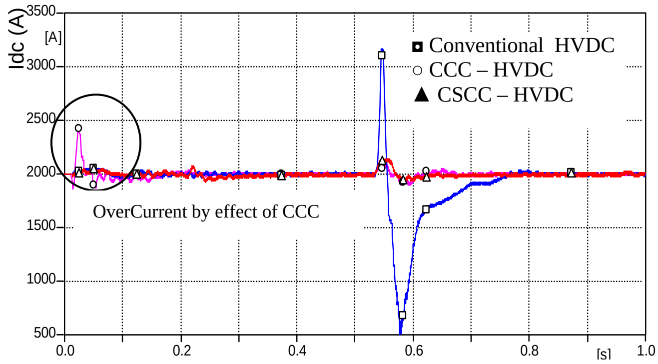

(c)

Fig. 11. (a) Idc (A), (b) Vac (kV) inverter side, (c) Idc (A). Compared between Conventional HVDC CCC-HVDC and CSCC-HVDC. All for Case 4.

The following Table I shows the levels and the rates of the Harmonics (THD) in inverter side for all models in Case 4. Additionally shows the Reactive Power compensation levels for the three systems.

TABLE I
Harmonics from the models

	Order				
Case (0%)	**11**	**13**	**23**	**25**	**THD%**
Conv.	846.1	655.14	450.48	392.1	1.0681
CCC	2352.1	1810.9	1463.6	1324	2.8830
CSCC	948.59	764.08	566.99	482.94	1.2848

Reactive power compensated

Conventional -HVDC	440 MVAR
CCC-HVDC	116 MVAR
CSCC-HVDC	74.38 MVAR

IV. ANALYSIS OF RESULTS:

In order to compare the results between conventional CIGRE HVDC model, CCC-HVDC and CSCC-HVDC three-phase failures were performed in the inverter considering different impedances of fault which affect the voltage levels (0%, 50%, 75% and 25%) respectively. For easier comparison of results, in Fig. 8, 9, 10 and 11, were overlapped the outputs from all models given in Fig. 6. For dc current the overcurrent in the first instants for HVDC with serial fixed capacitor and the performance between the fixed Capacitor and the Capacitor controlled by thyristor, the last model is more effective minimizing this overcurrent, such as shown the Fig. 11-a and Fig. 11-c, improving the voltage level response in the AC system of the inverter side, as shown in Fig. 11-b. minimizing the level of reactive power compensation shown in the Table I.

V. CONCLUSION

In this work was evaluated the transient behavior in conventional systems HVDC based on CIGRE Benchmark model, CCC-HVDC and CSCC-HVDC models. The CCC-HVDC mitigate the commutation problem presented in the conventional systems, decreases considerably the reactive power compensation level, however it produces over-current at the first moments and increases the levels of harmonics, as shown in Table I. The CSCC-HVDC have satisfactory behaviors, minimizes all defects in the case of fixed capacitor improves the voltage levels in AC and DC side during the failures, with a demand of 16.9% of the reactive power required by the Conventional HVDC. In addition it avoids the possible commutation failures and the subsynchronous resonance is limited by the control of the thyristors firing angle in the CSCC system.

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