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PERFORMANCE EVALUATION OF LINE AND CAPACITOR COMMUTATED CONVERTER BASED HVDC SYSTEM IN SIMULINK ENVIRONMENT

M. KHATIR, S A. ZIDI, S. HADJERI, M K. FELLAH, R. AMIRI

Electrical Engineering Department, ICEPS Laboratory,
Djillali Liabes University, BP 98 Sidi Bel Abbes 22000. Algeria

med_khatir@yahoo.fr

ABSTRACT

Most of HVDC systems consist of line commutated converters. The demand of reactive power is supplied by filter or capacitor banks which are connected on the primary side of the converter transformer. This conventional design is well known and proven during last decades. However, such conventional converters suffer commutation failures when they operate as inverter at a weak AC system. A series capacitor between converter transformer and thyristor valves (CCC: Capacitor Commutated Converter) can improve the immunity of inverter against commutation failure. Two concepts for the transmission with a high power capacity using HVDC technology are compared in this paper. These include the conventional and the CCC-inverters, connected to weak AC systems. The simulation results are presented using MATLAB/SIMULINK.

Keywords: *HVDC Transmission, Commutation Failures, CCC Inverter, Weak Receiving AC System*

1. INTRODUCTION

The conventional HVDC converters have a serious limitation in that they rely on the AC network voltage for the turn-off of the thyristor valves. This imposes a serious limitation particularly when the converter is applied in extremely long DC cable transmission or feeds a weak AC network.

The Capacitor Commutated Converter (CCC) has similar circuit topology to the conventional line commutated converter which is consisted of thyristor bridges. The difference between them is whether converter has series capacitor per phase, which is named commutation capacitor (CC) between converter transformer and thyristor bridge [1]. These capacitors give a voltage contribution to the valves allowing the use of smaller firing angles. The reactive power requirements of the CCC are therefore reduced, eliminating the need for switched shunt capacitor banks. This converter type appears less dependent on the AC network strength and more robust against network disturbances for successful valve commutation.

Fig.1 shows a schematic diagram of a basic six pulse CCC valve group, which is designed as a conventional converter equipped with series capacitors between the transformer and the valve in each phase. One important benefit is that the series capacitors are charged in a polarity that assists in the commutation process.

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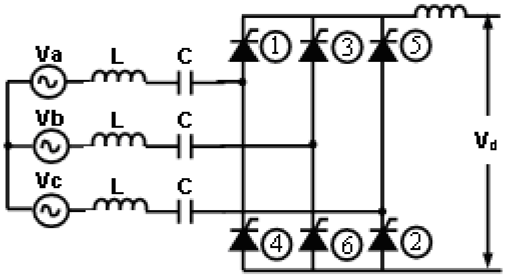


Fig 1. *Capacitor commutated converter (CCC)*

Two concepts for the transmission with a high power capacity using HVDC technology are compared in this paper. An evaluation of the transient performance using Matlab/Simulink is then conducted in order to examine the dynamic performance of these models with lower SCR. Results obtained confirms the superior performance of the CCC in applications involving weak AC systems.

2.THE CAPACITOR COMMUTATED CONVERTER

CCC is a conventional HVDC converter provided with commutation capacitors between the transformer and valves. The basic function of this concept is that the capacitors contribute to the valve commutation voltage. This contribution makes it possible to operate the CCC with much lower reactive power consumption compared to the conventional converter. Further, CCC gives a more robust and stable dynamic performance of the inverter station, especially when inverters are connected to weak AC systems and/or long DC cables. Increased commutation margins can be achieved, without increasing the reactive power consumption of the converter station, by reducing the capacitance of the commutating capacitors in order to increase their contribution to the commutation voltage. Fig. 2 shows the AC bus line-to-line voltage waveform and a-phase valve voltage waveform for the conventional and the CCC inverters respectively.

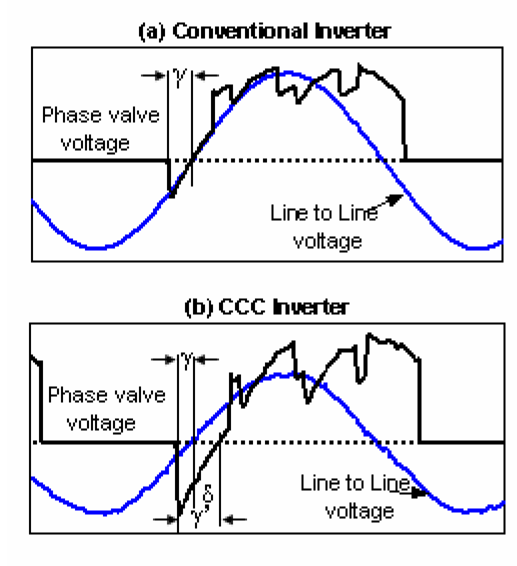


Fig 2. *AC bus voltage and valve voltage waveforms*

The extinction angle γ in Fig. 2 (a) is defined as the angle between the end of the commutation interval and the AC bus line-to-line voltage positive zero crossing, and is given by:

$$\gamma = \pi - (\alpha + \mu) \quad (1)$$

where α is the inverter firing angle, and μ is the overlap angle. However, after adding a series capacitor, the extinction angle becomes:

$$y' = \pi - (\alpha + \mu) + \delta \quad (2)$$

The commutation margin-angle γ' in the CCC inverter is the angle between the end of commutation and the valve voltage positive zero crossing. Where δ is the phase-lag angle between the AC bus voltage and thyristor valve voltage as shown in fig 2 (b). The increased commutation margin angle provides insensitivity to commutation failures. Successful commutation is possible even when the AC bus voltage drops.

3. THE CCC COMMUTATION DURING OVERLAP

Fig. 3 shows the equivalent converter circuit during commutation from valve 1 to valve 3.

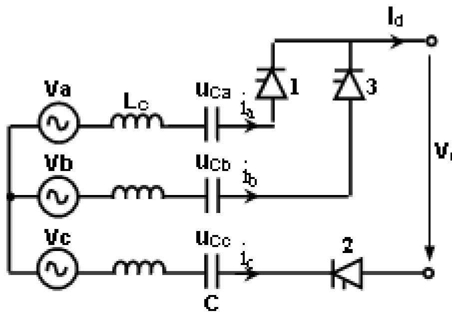


Fig 3. *Equivalent CCC circuit during commutation from valve 1 to valve 3 (non-conducting valves not shown)*

The instantaneous line-to-line voltages of the AC sources are taken as:

$$V_{ac} = V_a - V_c = \sqrt{3}\ V_m \cos(\omega t + 30°)$$
$$V_{ba} = V_b - V_a = \sqrt{3}\ V_m \cos(\omega t - 90°) \quad (3)$$
$$V_{cb} = V_c - V_b = \sqrt{3}\ V_m \cos(\omega t + 150°)$$

The mesh equation for the commutation loop from valve 1 to valve 3 is

$$V_b - V_a + u_{cb} - u_{ca} = L_C \frac{di_b}{dt} - L_C \frac{di_a}{dt} \quad (4)$$

Using equation (3) and taking into account that the direct current is constant this can be written as:

$$\sqrt{3}\ V_m \sin(\omega t) + u_{cb} - u_{ca} = 2L_C \frac{di_b}{dt} \quad (5)$$

Under normal operating conditions, the capacitors in phase (a) and (b) are charged in such a way as to accelerate the commutation. Unfortunately, the capacitor voltages themselves depend again on the current i_b:

$$C\frac{du_{ca}}{dt} = -i_a = i_b - I_d \quad (6)$$

$$C\frac{du_{cb}}{dt} = -i_b \quad (7)$$

An analytical solution is presented in [2]. A much simpler solution which is nonetheless quite accurate will therefore be developed here based partly on [3]. We have assumed by symmetry that the capacitors charge to a maximum/minimum voltage of $+\hat{V}_C / -\hat{V}_C$.

The total excursion of capacitor voltage from peak to peak is:

$$\hat{V}_C = \frac{\pi}{3\omega C} I_d \quad (8)$$

Integrating equation (5) over the interval of overlap and inserting the boundary conditions $i_b(\omega t = \alpha) = 0$ and $i_b(\omega t = \alpha + \mu) = I_d$ yields

$$\frac{\sqrt{3}\ V_m}{2\omega L_C I_d}(\cos\alpha - \cos(\alpha + \mu)) + \frac{\mu}{6\omega^2 L_C C}(2\pi - \mu) = 1 \quad (9)$$

This equation is transcendental and needs to be solved for μ numerically. However, it can be further simplified by approximating $\cos(\alpha + \mu)$ whit a second-order Taylor series:

$$\cos(\alpha + \mu) \approx \cos\alpha - \mu \sin\alpha - \frac{\mu^2}{2}\cos\alpha \quad (10)$$

Equation (9) then reduces to a quadratic equation in μ with the solution

$$\mu \approx \frac{\sqrt{4A + B^2} - B}{2A} \quad (11)$$

Where

$$A = \frac{\sqrt{3}\ V_m}{2\omega L_C I_d} \cdot \frac{\cos\alpha}{2} - \frac{1}{6\omega^2 L_C C} \quad (12)$$

$$B = \frac{\sqrt{3}\ V_m}{2\omega L_C I_d} \cdot \sin\alpha + \frac{2\pi}{6\omega^2 L_C C} \quad (13)$$

4. SYSTEM MODELING

Using the conventional and the CCC-inverter technology, design and modeling of a transmission system with a rated power capacity of 1000 MW (500 kV, 2 kA) over a distance of 300 km (overhead line) is described in this paper. The two models should meet transient performance of both systems.

4.1 AC/DC system strength

A CIGRÉ document released in 1992 [4] provides valuable to the understanding the AC/DC interactions. Their influence on station design and performance is assessed with reference to the AC-DC system strength, a relative term which is generally expressed by the short-circuit ration (SCR), i.e, the ratio of the AC system short-circuit capacity to DC link power:

$$SCR = \frac{S}{P_{dc}} \quad (14)$$

where S is the AC system three-phase symmetrical short-circuit level in megavolt-amperes (MVA) at the converter terminal AC bus with 1.0 pu AC terminal voltage, and P_{dc} is the rated DC terminal power in megawatts (MW). However, the SCR concept has to be used with caution when considering different types of interactions, because the shunt capacitors including AC filters connected at the AC terminal of a DC link can significantly increase the effective AC system impedance. To allow for this, the effective short-circuit ratio (ESCR) is defined as follows:

$$ESCR = SCR - \frac{Q_C}{p_{dc}} \quad (15)$$

where Qc is the value of three-phase fundamental Mvar in per unit of P_{dc} at per unit AC voltage of shunt capacitors connected to the converter AC bars (AC filters and plain shunt banks). The following SCR and ESCR values can be used to classify an AC system:

a) a strong AC system is categorized by an SCR ≥ 3 , (ESCR ≥ 2.5).

b) a weak AC system is categorized by 2 ≤ SCR < 3, (2.5 > ESCR ≥ 1.5).

c) a very weak AC system is categorized by an SCR < 2, (ESCR < 1.5).

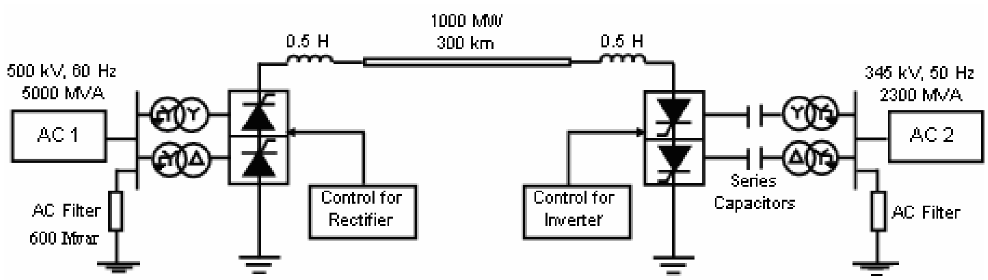


Fig. 4. *HVDC system model (shown with CCC option)*

4.2 Conventional HVDC system

The conventional HVDC system rectifier is connected to a very strong sending end (SCR = 5), whereas the inverter is connected to a relatively weak receiving AC network (SCR=2.3). The converter transformers (YY and YΔ) have a leakage reactance of 0.15 pu. The tap position is rather at a fixed position determined by a multiplication factor applied on the primary nominal voltage of the converter transformers (0.9 on rectifier side; 0.96 on inverter side). The AC networks, both at the rectifier and inverter end, are modelled as infinite sources separated from their respective commutating buses by system impedances.

The impedances are represented as L_2-R//L_1 networks having the same damping at the fundamental and the third harmonic frequencies. The impedance angles of the receiving end and the sending end systems are selected to be 80 degrees. This is likely to be more representative in the case of resonance at low frequencies [5].

4.3 CCC system

The CCC transmission system has the same conventional rectifier AC side. However, the CCC-inverter scheme is similar in its design, but differs in reactive compensation and control parameter settings. The configuration of this system is given in fig. 4. In contrast to the conventional HVDC transmission system the reduced extinction angle, due to the additional commutation voltage supported by the CC, leads to a decreased consumption of reactive power. So the AC filter capacitors can be smaller and the quality of the filters can be improved. It is practical to limit the size of the capacitors to a value allowing extending the firing angle range at the inverter up to 180° [6].

The capacitance of the CC used in this model is determined to C = 72 μF [7]. The values for the rated DC voltage and current are equal to the design of the conventional HVDC. The two concepts (conventional and CCC) have the same SCR at the inverter side. However, each concept has different ESCR since the total reactive power generated in the filters and shunt capacitors at the inverter bus Q_C is different in each concept. As may be seen from Table 1, the ESCR for the CCC-inverter is significantly larger compared to the conventional, due to the fact that the CCC has a lower reactive power installation at its inverter bus. This indicates that the CCC ought to have a superior performance over the conventional option. However, the additional dynamics associated with the series capacitors could compromise this expected improvement.

HVDC SYSTEM	P_{DC} (MW)	GENERATION Q_C (MVAR)	SCR	ESCR
Conventional	1000	600	2.3	1.7
CCC	1000	150	2.3	2.15

Table 1. *SCR and ESCR in each HVDC system model at the inverter side*

4.4 Control systems

In the conventional HVDC scheme, the rectifier and the inverter control both have a voltage and a current regulator operating in parallel calculating firing angle α v and α i. Both regulators are of the proportional and integral type (PI). In normal operation, the rectifier controls the current at the Id_ref reference value whereas the inverter controls the voltage at the Vd_ref reference value. The I_margin and Vd_margin parameters are respectively 0.1 pu and 0.05 pu.

Another important control function is implemented to change the reference current according to the value of the DC voltage. This control named Voltage Dependent Current Order Limits (VDCOL) automatically reduces the reference current (Id_ref) set point when VdL (Vd line) decreases (as for example, during a DC line fault or a severe AC fault). Reducing the Id reference currents also reduces the reactive power demand on AC network, helping to recover from fault [8],[9]. The CCC-HVDC scheme can work with conventional control system, with minimum modification [10].

5. SIMULATION RESULTS

Conventional and CCC-HVDC inverter are compared with respect to their transient behaviour. The frequency response of the AC systems (inverter side), and the following types of disturbances are investigated in this paper:

1. Single phase-to-ground fault at inverter side of the conventional and the CCC-inverter system.
2. Remote single phase-to-ground fault at inverter side of the conventional and the CCC-inverter system.

For each of the transient case considered above, plots of inverter DC voltage, inverter DC current, inverter firing angle, and inverter valves current of two Graetz bridges connected in series (YY and YΔ), are given.

5.1 Frequency response of the AC systems

Fig.5 shows the magnitude, seen from the busbar where the filter is connected, of the combined filter and AC network impedance as a function of frequency.

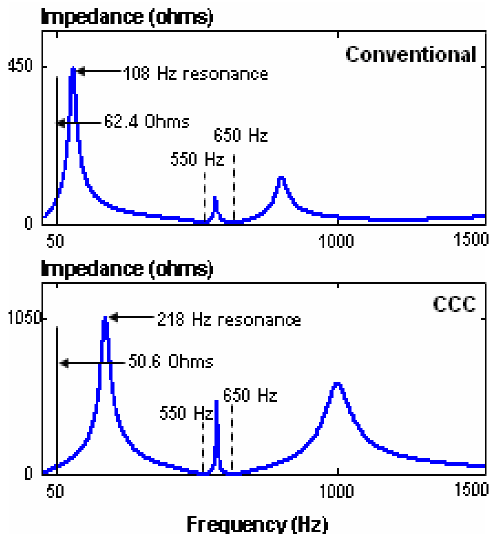


Fig 5. *Positive-sequence impedances of the two AC networks (Conventional and CCC-inverter respectively)*

Notice the two minimum impedances on the Z magnitudes of the AC systems, these series resonances are created by the 11th and 13th harmonic filters. They occur at 550 Hz and

650 Hz on the 50 Hz. It is clearly evident a parallel resonance very closes to the 2nd harmonic at 103 Hz on the conventional inverter side. This could cause high stresses in converter equipment and AC harmonic filters, for some types of disturbances.

The use of CCC concept has, in general, the effect of increasing the range of the resonance frequencies at the AC system side. The low principal natural frequency, coinciding whit the parallel resonance at 207 Hz on the CCC-inverter side, is a determining factor in the development of overvoltages and interaction with the DC system.

5.2 Single phase-to-ground fault at inverter side

A single phase-to-ground fault was applied to the A-phase of the inverter bus, and the duration of the fault was 5 cycles. Fig.6 shows the recovery performance following the single-phase fault of both the conventional and the CCC inverter based scheme. When this fault is applied at the conventional inverter at t = 0.8 s, due to a reduction in AC voltage of the inverter bus, commutation failures will accrue. The DC current therefore shoots up, and the DC voltage decreases. The VDCOL operates and reduces the reference current to 0.3 pu. The conventional inverter valves current plots indicate a number of commutation failures of the corresponding valve groups, which translates by an increase in the DC current because the valves 2-5 in the YY and YΔ bridges are conducting current at the same time, and that the two Graetz bridges are short-circuited on the DC side. For the CCC-inverter, commutation failures will accrue during the recovery in the two bridges (YY and YΔ). All oscillations (100 Hz) in the DC voltage and current at both conventional and CCC systems, means that the phase voltages and currents at both AC systems are unbalanced.

5.3 Remote single phase-to-ground fault at inverter side

A remote single phase-to-ground fault was simulated by grounding the A-phase of the inverter bus through (80 Ohm) resistance. The duration of the fault was 5 cycles. Results of this transient study are shown in fig. 7. The fault is applied at t = 0.8s. This is the most typical type of fault that occurs in overhead lines and is by Thio et al [11] considered more severe than a three phase-fault in terms of commutation failure. The reason for this is due to the fact that the single-phase faults result, contrary to the balanced three-phase fault, in phase-shifts in the zero-crossings of the commutation voltages. These phase-shifts decrease the commutation margin for some of the thyristor valves and increase it for other valves.

The results for the single-phase remote fault show that the conventional inverter valves current plots indicate a number of commutation failures of the corresponding valve groups, which translates by an increase in the DC current because the valves 5-2 in the (YY) bridge, and 1-4 in the (YΔ) bridge are conducting current at the same time, and that the two bridges are short-circuited on the DC side. The DC current therefore shoots up (1.9 pu); the VDCOL operates and reduces the reference current to 0.3 pu. When the fault is cleared at t = 0.9 s, the DC voltage starts to increase with oscillation (around 100 HZ). Following commutations take place in a normal way, and normal operation is resumed. The system recovers in approximately 0.1 s after fault clearing. The recovery time is defined as the time from fault clearing to the instant at which 90% of the pre-fault DC power is restored. However for to the CCC-inverter, we can see that the nominal operation of the DC transmission is not affected by this fault.

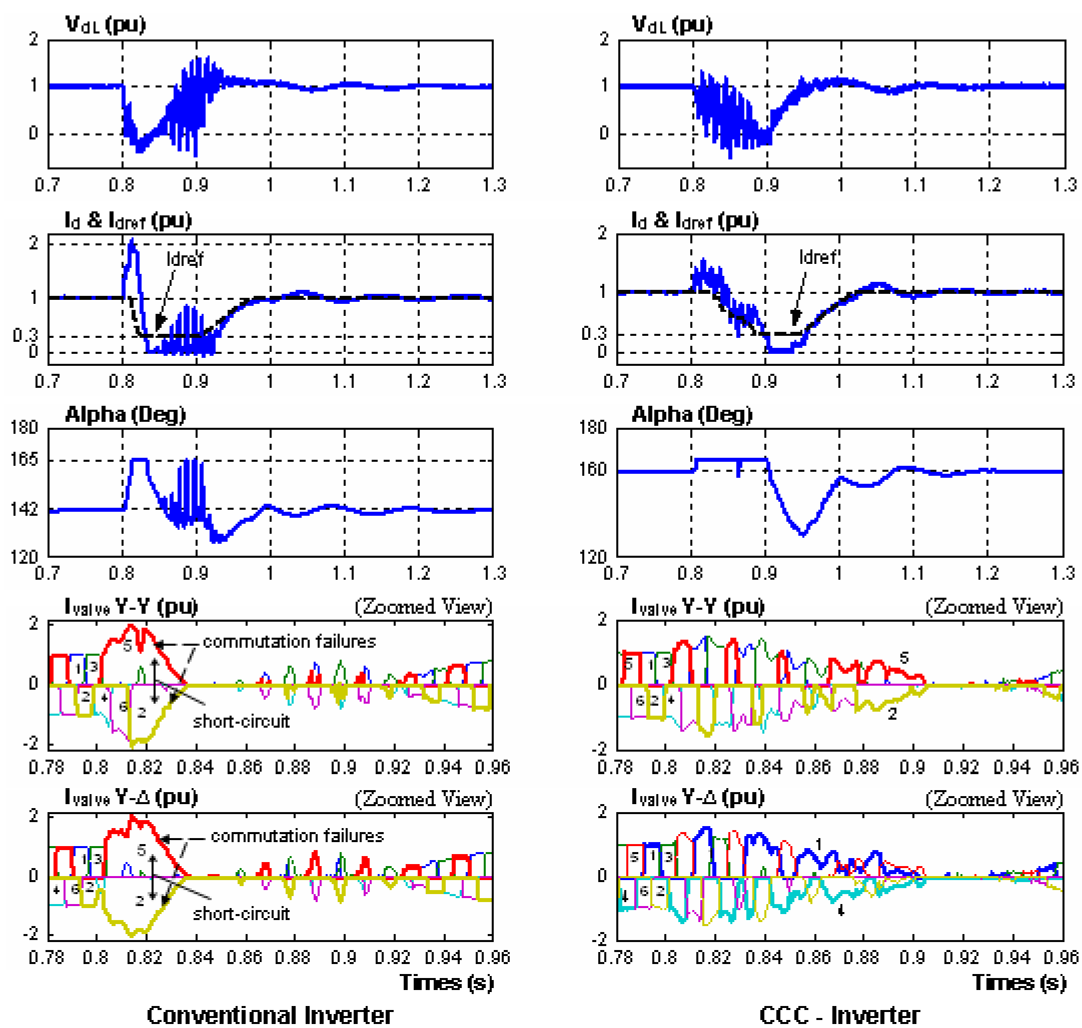


Fig 6. *Single phase-to-ground fault at inverter*

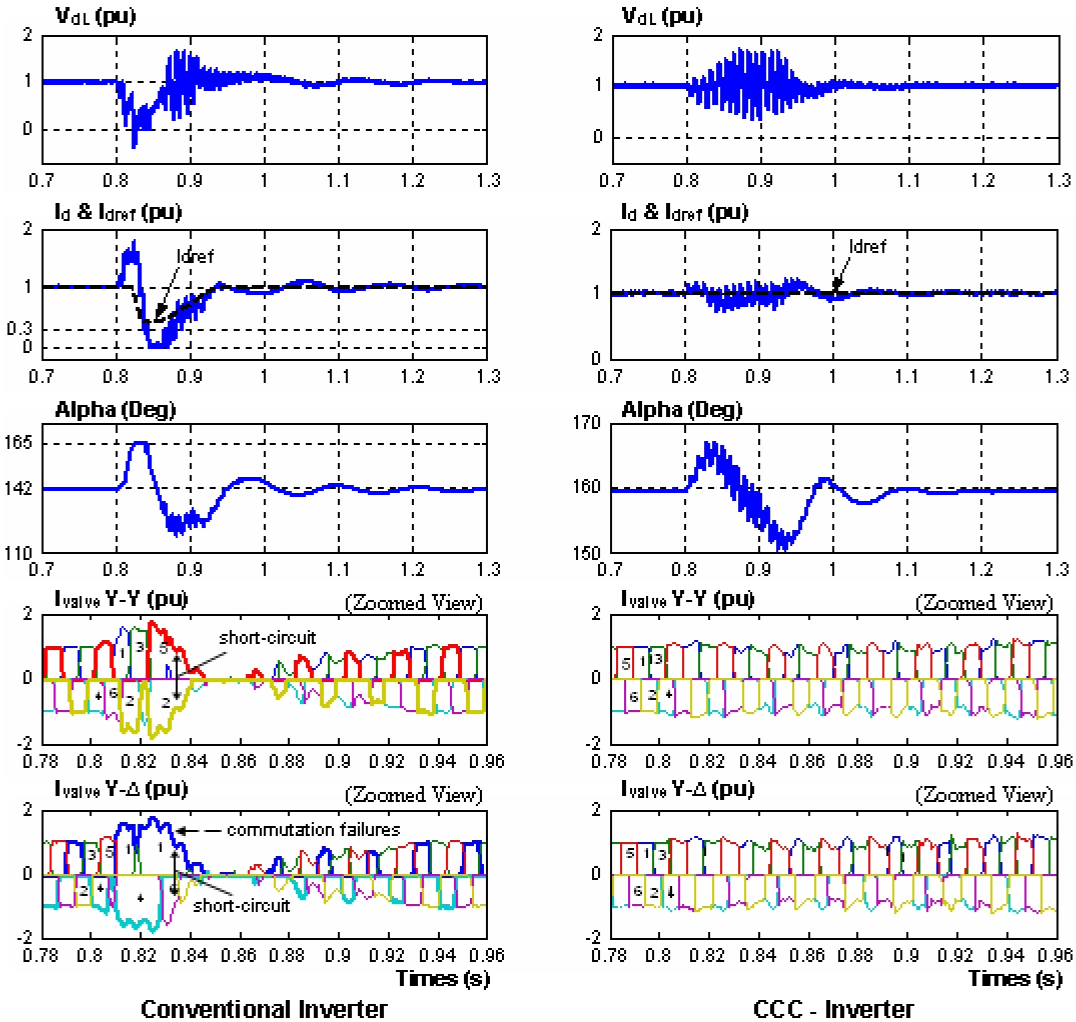


Fig 7. *Remote single phase-to-ground fault at inverter*

6. CONCLUSION

The transient behaviors of the CCC and conventional inverter feeding weak AC systems were compared by modeling these schemes using PSB/Simulink.

The capacitor commutated converter has many beneficial features that make it attractive for use in an HVDC transmission system connected to a weak receiving AC system. The effectiveness of these features can be studied using steady-state and transient analyses. The transient analysis shows that the CCC-HVDC system demonstrates a good behavior than with conventional technology following a single phase-to-ground and a remote single phase-to-ground fault at a weak receiving AC network. The increased commutation margin-angle provides insensitivity to commutation failures. Successful commutation is possible even when the AC bus voltage is close to zero. However, commutation failures occur when the AC bus voltage is recovered.

Appendix

Data for the system model:

Rectifier end:

The rectifier end AC system representing a strong system (SCR = 5), consists of one source with an equivalent impedance of: R = 26.07 Ω , L_1 = 48.86 mH, L_2 = 98.03 mH.

Conventional Inverter:

The conventional inverter end AC system representing a weak system (SCR = 2.3), consists of one source with an equivalent impedance of: R = 26.978 Ω , L_1 = 60.695 mH, L_2 = 121.739 mH. V_{dL} = 500 kV, I_d = 2 kA, α = 142º. Transformer (each): 600 MVA, leakage =15%.

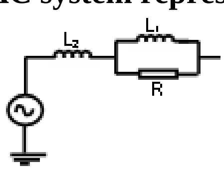
CCC Inverter:

The CCC-inverter end AC system representing a weak system (SCR = 2.3), consists of one source with an equivalent impedance of: R = 26.978 Ω , L_1 = 60.695 mH, L_2 = 121.739 mH. V_{dL} = 500 kV, I_d = 2 kA, α = 160º, leakage =15%. C= 72 µF/phase.

DC line parameters:

R_{dc} = 0.015 Ω /km, L = 0.792 mH/km, C = 14.4 nF/km

Details of AC system representation:



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KHATIR Mohamed was born in Ain Témouchent, Algeria, in 1977. He received the Eng. degree in electro technical engineering, and the Master's degrees from the Djillali Liabes University of Sidi Bel-Abbes (Algeria), in 2002 and 2006 respectively. He is now a PhD Candidate in the Electrical Engineering Department of Djillali Liabes University. His main field of interest includes HVDC and FACTS.