ELEKTROTEHNIŠKI VESTNIK 90(4): 183–190, 2023
ORIGINAL SCIENTIFIC PAPER

Enhancement of the HVDC LCC system protection by using an integrated DC/DC converter

Sofiane CHIHEB[1], **Badri Rekik**[1],**Tarek Messikh** [1], **Omar Kherif**[2]

[1]*National Higher School of Technology and Engineering ENSTI, Annaba, 23000, Algeria*
[2]*Advanced High Voltage Engineering Research Centre, Cardiff School of Engineering, Cardiff CF24 3AA, U.K.*
Email:s.chiheb@ensti-annaba.dz

Abstract. The paper investigates the response of the High-voltage Direct Current (HVDC) CIGRE Benchmark when exposed to overvoltages, voltage drops, or missed pulses in power converters. The impact of operation of integrated DC/DC converters is evaluated. A system using MATLAB/Simulink is simulated at faulty states to evaluate the HVDC link behaviour and reestablish the HVDC link after fault removal. A commutation failure in the HVDC system occurs when the AC voltage perturbation above than 10 %, at which the coil voltage significantly increased and interrupts the current in thyristors. To solve the problem, a DC/DC converter of the Buck configuration is integrated into the DC filters. The converter pulse is controled using the PWM technique where the pulse width is adjusted to maintain the DC voltage within the set of limits. Using the DC/DC converter, the commutation failure is eliminated upon fault disappearance. Moreover, there is no need for communication between the HVDC poles and the protection against faults in the HVDC system is ensured.

Keywords: HVDC, power electronics; thyristor, power transmission, commutation failure.

Izboljšava zaščite sistema HVDC LCC z uporabo integriranega DC/DC pretvornika

V prispevku obravnavamo odziv visokonapetostnega enosmernega toka (HVDC) CIGRE Benchmark ob izpostavljenosti prenapetostim, padcem napetosti ali zgrešenim impulzom v močnostnih pretvornikih. Sistem, ki uporablja MATLAB/Simulink, smo simulirali v primeru okvar z namenom ocenitve obnašanje povezave HVDC in ponovne vzpostavitve povezave HVDC po odstranitvi napake. Okvara pri komutaciji se pojavi v sistemu HVDC, ko je motnja izmenične napetosti nad 10 %, pri kateri se napetost tuljave bistveno poveča in prekine tok v tiristorjih. Okvaro smo odpravili z vgradnjo integriranega pretvornika DC/DC v enosmerna sita. Pretvornik smo krmilili s tehniko PWM, kjer je širina impulza prilagojena za vzdrževanje enosmerne napetosti znotraj nastavljenih meja. Z uporabo DC/DC pretvornika smo odpravili okvaro, pri čemer ni potrebe po komunikaciji med poli HVDC.

1 INTRODUCTION

Many HVDC transmission systems operate to transport the electric energy transmission when the AC transmission capacity is exceeded (synchronism, distance, stability . . .) [1]-[4]. This technology uses power electronic systems to convert the electric energy from AC to DC form in the first power grid. After being transmitted, the energy is converted again to the AC form to be injected into the second AC power grid. Two main types of the electronic power converters are used [2]: the Line Commutated Converter (LCC) and Voltage Source Converter (VSC).

Because of its many advantages (large capacity, high voltage rating, . . .), the LCC technology is widely used to interconnect the power grids [5].So far, the performance of the VSC converters in the HVDC transmission systems has been studied. Langwasser et al. [6] calculated the fault current in the back-to-back HVDC system considering the control dynamics. [7] proposed strategies to protect the HVDC system against faults by estimating the fault current and comparing the functioning of several interruption schemes at a fault occurrence. Wu et al. [8] study the HVDC system to evacuate the electric energy generated from Offshore Wind-Power Plant. The system combines VSC converters and a DC Chopper. In [9], three case studies investigate the fluctuation of fault currents and proposed each HVDC system to be controlled. [10] studies the contribution of VSC with a Modular Multilevel Converter (MMC) at a short circuit current to define its dependence on the control parameters order to evaluate and avoid the short-circuit current.

[11] proposes a hybrid installation between HVAC and HVDC and between LCC and VSC [12] to improve the system behaviour in occurrence of faulty current state.

Numerous investigations have been done to integrate the DC/DC converters in the HVDC grids. Alagab et al. [13] compare single and multi-stage converters by integrating Marx principle into the HVDC system. Zhang et al. [14] integrate the DC/DC converter into

---

Received 25 July 2023
Accepted 17 October 2023

a HVDC system with ability to react against a short-circuit fault. Qin et al. [15] proposed A multiport DC-DC converter with MMC converter to interconnect the HVDC systems enabling an energy exchange between the HVDC grids. Kish et al. [16] proposed multi level DC/DC converter into the MMC HVDC system to interconnect several HVDC systems with the possibility of bidirectional control of the load flow, interconnection of several voltage grids and fault protection on the DC side. [17] provides an overview for the DC/DC converters used in the HVDC systems. Based on the converters structure, Páez et al. [17] clasify the DC/DC converters in terms of their form to specify the requirements for each converter and show the advantages of using the HVDC interconnection.

The paper studies the behaviour of the HVDC LCC GIGRE Benchmark by varying the grid AC voltage value. The initial rectifier/inverter control is kept unchanged to investigate the behaviour of the HVDC systems. The missed impulse condition is examined. One of the thyristors receives no impulse from control system to evaluate the HVDC system behaviour. To improve the HVDC system reliability, DC/DC converters of the Buck configuration are used at the ends of the DC grid side. The proposed DC/DC converters are controlled by the PWM strategy to avoid the link interruption and to reestablish the system operation with no intervention by the rectifier or the inverter connected to the system.

The proposed DC/DC converters do not depends on the HVDC control from the feedback required from the other side of the HVDC link. which to the authors knowledge haven't been studied. The simulations are made using the MATLAB/Simulink.

The paper is structured as follows. Section 2 presents the CIGRE Benchmark model, i.e the proposed DC/DC converter integration. Section 3 studies the behavior of the HVDC benchmark under the studied fault conditions, the impact of the DC/DC implementation on the HVDC LCC system and discusses the obtained results. Section 4 draws conclusions of our work.

2 STUDY OF THE CIGRE BENCHMARK AND INTEGRATION OF A DC/DC CONVERTER

2.1 *CIGRE benchmark system*

Fig. 1 shows HVDC benchmark proposed by CIGRE [18]. It consists of a monopolar 500 kV line transporting 500 MW with an LCC converter of 12 pulses. The frequency of AC grids is 50 Hz and the Short-Circuit Ratio (SCR) is 2.5. The reactive power is compensed by a capacitor (0.125 p.u.) and AC filters (2*0.25 p.u.). The details are given in [18].

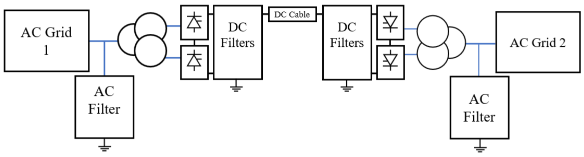


Figure 1. single line diagram of the CIGRE HVDC benchmark system

The LCC system: the rectifier mean voltage (V_{DC}) is given in [2]:

$$V_{DC} = \frac{3\sqrt{2}}{\pi} V_{AC1} cos\alpha \; - \frac{3}{\pi} X_{AC1} I_{DC} \qquad (1)$$

where V_{AC1} is a phase-to-phase RMS voltage (in the transformer secondary winding connected to power grid 1), α is the rectifier firing angle, X_{AC1} is the commutation reactance due to the induction effect in power grid 1 and I_{DC} is the mean DC current given in [2]:

$$I_{DC} = \frac{V_{AC1}}{\sqrt{2} X_{AC1}} (cos\alpha + cos(\alpha + \delta)) \qquad (2)$$

δ is the commutation angle caused by the AC system reactance.

The reactive power (Q_{rect}) consumed by the rectifier is given in [2]:

$$Q_{rect} = P_{rect} \;\; tan\alpha \qquad (3)$$

P_{rect} is the active power transmitted through the converter.

When back to the inverter side, these relations are used by substituting angle α by γ [2].

The parameters are implemented in the simulated system in MATLAB/Simulink.

2.2 *Fault conditions for the CIGRE HVDC benchmarking*

The HVDC system is simulated at AC grid voltage variation and converter missed pulses.

For the AC grid voltage variation, two cases are simulated: the overvoltage applied to AC grid 1 (Source), and the voltage decrease applied to AC grid 2 (load). The converter pulse angles are kept invariable to evaluate the performance of the CIGRE HVDC benchmark to resist to eventual AC grid voltage variations.

The variations made are as follows: for power grid 1, the voltage is varied five times from its nominal value 1 p.u. to : 1.04, 1.08, 1.12, 1.16 and 1.2, respectively, at the times 0.25, 0.75, 1.25, 1.75 and 2.25 seconds. The duration of the new voltage value is 0.25 seconds. The voltage is then returns to its initial value (see Figure 2 (a)). For AC grid 2, the voltage is varied from 1 p.u. to: 0.96, 0.92, 0.88, 0.84 and 0.8, respectively, at the times 0.25, 0.75, 1.25, 1.75 and 2.25 (see Figure 2(b)).

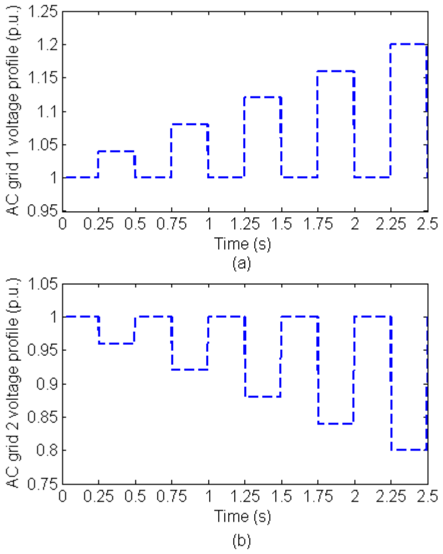
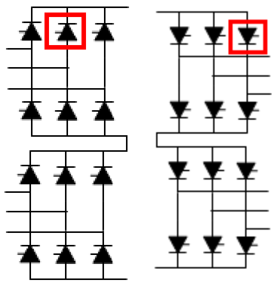


Figure 2. Voltage value variation applied to the HVDC system: (a) AC voltage variation applied to AC grid 1, (b) AC voltage variation applied to AC grid 2.

The pulses missed in the HVDC converters are supposedly due to the fact that one of the converter thyristors receive no pulses for 0.2 seconds (one period). The system ability to continue its initial function without any reaction of the control system is verified by simulating the first pulse interruption of one of the rectifier thyristors and then for one of the inverters thyristors. The location of the thyristors with missed pulses for one period are shown in Figure 3 (a) for the rectifier side, and in (b). The pulse interruption simulation between 0.5 and 0.52 seconds. The inverter thyristor pulse is been interrupted between 1 and 1.02 seconds.



(a) (b)

Figure 3. Thyristors missed pulses in (a) the rectifier and (b) the inverter

2.3 *Using a DC/DC converter in the CIGRE HVDC benchmarking*

The PWM DC/DC converter is used to improve the HVDC system reliability by using the DC filter elements.

The buck configuration of DC/DC converter is used because of its similarity between the L and C positions to the source and the load, with the L and C position in the DC filter used in the HVDC LCC system. The conventional Buck DC/DC converter consists of a controlled switch (S), diode (D), inductor (L) and capacitor (C) [19].

For the conventional buck converters, when switch (S) is closed, diode (D) is blocked, and with switch (S) open, the diode conducts to support an uninterrupted current in the smoothing reactor. Switch (S) and diode (D) are placed as shown in Figure 4. Applying pulses to the switch is controlled by using a closed loop .

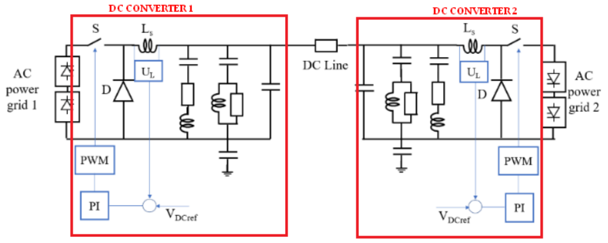


Figure 4. DC/DC converters integrated in the global HVDC system.

In the proposed HVDC system, the smoothing reactor voltage is an important parameter. If it is greater than the rectifier one (or the inverter one), the thyristor may be blocked and a commutation failure may occur. To avoid it, a DC/DC control strategy is used to dissipate the smoothing reactor energy in other DC filter elements.

In the DC/DC converter of a buck configuration (step-down), the switch is closed for period T. The value of the output voltage is approximately that of the input. When the switch is opened, the output voltage is zero, however reactor L is discharged through the capacitor and the load through the diode.

To ensure the continuity of the circuit, a closed loop is used to compare the load voltage with its reference value. The error signal passes through a PI controller to give the pulse duration to the PWM block.

The task of our HVDC system, are to maintain the load flow through the DC side and to eliminate the energy stored in the smoothing reactors at a fault occurrence.

This is achieved by keeping the voltage applied by the smoothing reactors lower than the DC nominal voltage, thus keeping the current passing from the rectifier to the inverter, and the energy stored in the reactors during faults must be evacuated and generated during transient states.

Unlike to the conventional PWM converters, where the period is fixed and the duration angle (considered θ) varies according to the PWM controller, in our DC/DC converter the switch is opened when reactor potential

U_{Ls} is higher than nominal DC value U_{DC}, and the power supply is interrupted. When the switch is open, the accumulated smoothing reactor energy is dissipated in other DC filter elements through diode D. The current in the inductance is now changed and the switch is kept open until the reactor voltage is lower than the nominal DC voltage. So, our DC/DC converter keeps the duration t_{on} fixed and varies the period T according to the flowchart of the PWM control shown in Figure 5.

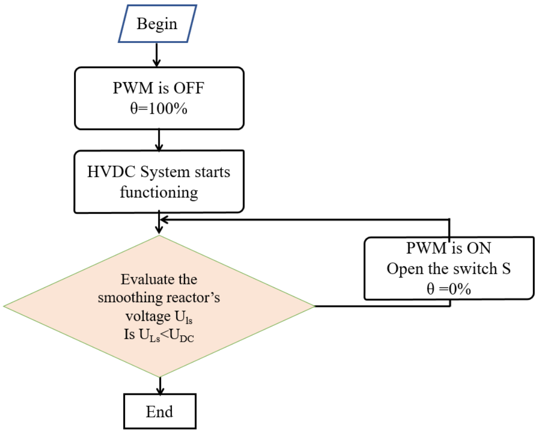


Figure 5. PWM control algorithm flowchart for the DC/DC converter integrated in the HVDC system.

3 RESULTS AND DISCUSSION

3.1 *Impact of the AC grid voltage variation*

3.1.1 Impact of the AC grid 1 voltage increase: The first to be assessed on those effects of the voltage increase on AC grid 1. The voltage is gradually increased on AC grid in five steps by 4%, 8%, 12%, 16%, and 20%. Their duration is 0.25 seconds before turning back to its nominal value.

The simulation evaluates the ability of the HVDC LCC system to resist to significant voltage variations. The parameters simulation results for both the AC grids and the DC system under voltage variations in AC grid 1 are given in Figure 6.

The HVDC system remains relatively unaffected by the voltage increase by 4%, 8%, and 12% in AC grid 1. The system restores its initial state conditions once the voltage returns to its nominal value. However, when the voltage in AC grid 1 increases up to 1.16 and 1.20 p.u., a short circuit occurs in both the DC side and AC grid 1. A observe voltage and current deformation observed in AC grid 2 is likely to be due to a commutation failure in the converters.

3.1.2 Impact of the AC grid 2 voltage increase: We are particularly interested to study the consequences of decreasing the nominal voltage on the AC grid 2 in four steps by reducing 4%, 8%, 12%, 16% and 20%. Each voltage reduction again takes 0.25 seconds before being restored to its nominal value. The results obtained for the voltage and current for both grids are given in Figure 7.

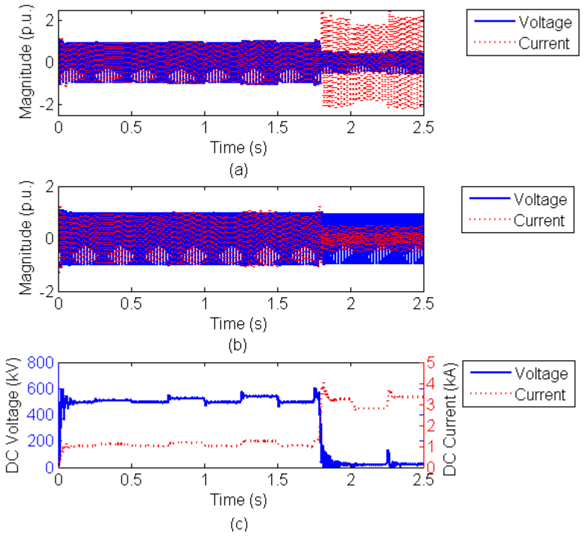


Figure 6. Impact of AC grid 1 voltage increase on the CIGRE HVDC benchmark : (a) AC grid 1 voltage and current for one phase; (b) AC grid 2 voltage and current for one phase; (c) DC side voltage and current.

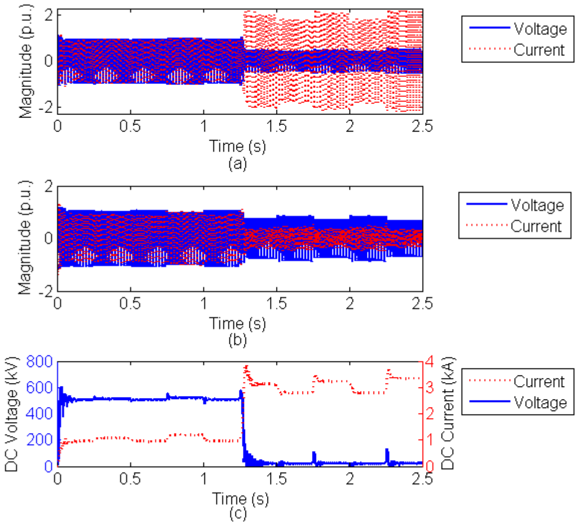


Figure 7. Impact of the AC grid 2 voltage drop on the CIGRE HVDC benchmark : (a) single-phase voltage and current for AC grid 1; (b) single-phase voltage and current for AC grid 2; (c) DC voltage and current.

The simulation results show that the voltage decreases 4% and 8% does not disturb the functioning of the HVDC link. However, when the voltage decreases to 88% (a drop of 12%) and lower, a commutation failure in the HVDC link with a short-circuit in AC grid 1 and

DC side is observed. Moreover, the voltage and current waves of AC grid 2 are distorted.

3.1.3 Impact of the missed pulses: To simulate the missed pulses, the rectifier pulse is interrupted between 0.5 and 0.52 seconds and the inverter thyristor pulse between 1 and 1.02 seconds (see Figure 3). The DC side voltage and current obtained by interrupting pulse are shown in Figure 8.

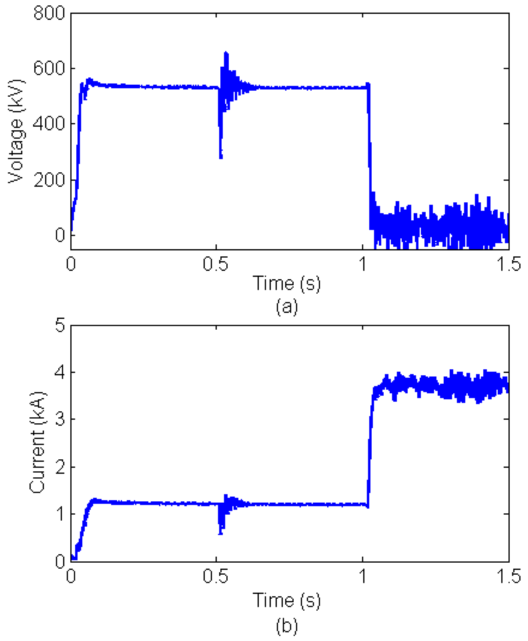


Figure 8. Parameters obtained with a missed pulse:(a) DC voltage, (b) DC current.

After the rectifier pulse interruption, a slight perturbation in the DC voltage and current value. The system can reestablishes the commutation by submiting the pulses the the rectifier thyristors.

At the inverter pulses, a short circuit occurs on the DC side due to a commutation failure in the inverter.

3.2 Impact of the integrated DC/DC converter

3.2.1 Impact of the integrated DC/DC converter on the voltage increase in AC grid 1: Simulation of the faults occuring on the AC and DC side and in converters with no control system shows the HVDC LCC system may be perturbed and a short-circuiting fault developed if the control system doesn't work. For the control system to operate correctly, the communication between the HVDC poles should be well done (rectifier and inverter). The lack of any information generates a risk of a short-circuit occurrence in the HVDC system. To avoid it, we propose to use a PWM DC/DC converter inspired by the Buck converter configuration with our HVDC system.

Since the major problem in the HVDC system is the energy stored in the smoothing reactor, we propose to convert the DC filter into a buck converter to limit the magnetic energy in the smoothing reactor.

After integrating the DC/DC converter in the HVDC system, the impact of the voltage increase is evaluated in the same steps and duration as in the first simulation.

Figure 9 shows for the AC grid 1, DC side and AC grid 2 parameters obtained by using the DC/DC converter.

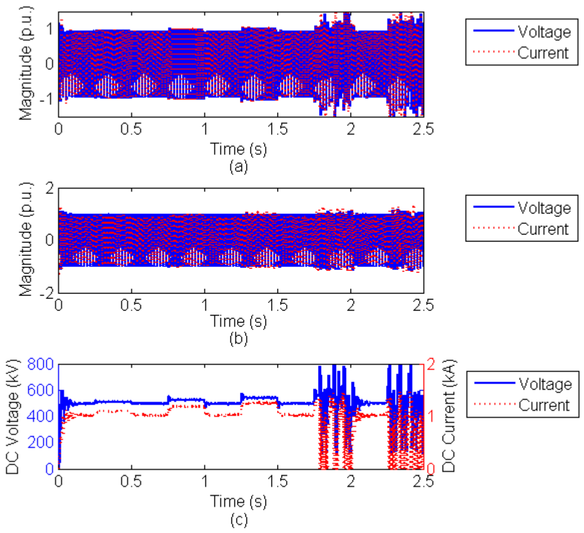


Figure 9. Impact of the DC/DC converter on the HVDC system by using the AC grid 1 voltage: (a) the AC grid 1 voltage and current for one phase; (b) the AC grid 2 voltage and current for one phase; (c) the DC side voltage and current.

With no DC/DC converter it is difficult for the HVDC system to maintain the HVDC link stability in the presence of overvoltages, especially at an increase by 16 and 20% in the AC grid 1 voltage.

Using the DC/DC converter, there are some interruptions in the DC voltage and current at overvoltages when the HVDC system resumes its functionality after the overvoltages are removed.

3.2.2 Impact of using the DC/DC converter at an AC grid 2 voltage drop: The impact of the proposed PWM DC/DC converter on the HVDC system is verified at a voltage drop in AC grid 2. The AC grid 2 voltage decreases in five steps by -4%; -8%; -12%; -16% and -20%, in the same duration as in the previous simulation.

Figure 10 shows the AC grid 1, DC side and AC grid 2 parameters obtained when using the DC/DC converter at a voltage decrease in AC grid 2.

With no DC/DC converter, the HVDC system can't reestablish the commutation after the voltage drop between 12 and 20 % of the nominal voltage (Figure 7) as a result of an excessive voltage applied by the smoothing reactors. With the DC/DC converter, the control system generates pulses to the switches which decreases the smoothing reactor voltage and reestablishes the HVDC system.

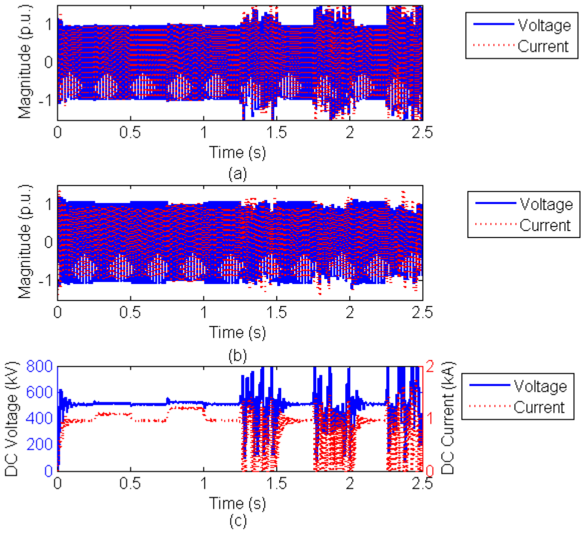


Figure 10. Impact of using a DC/DC converter integration in the presence of the AC grid 2 voltage variation: (a) single-phase voltage and current for AC grid 1; (b) single-phase voltage and current for AC grid 2; (c) DC voltage and current.

3.2.3 Impact of using the DC/DC converter at missed pulses: The contribution of the DC/DC converter in the HVDC systems at missed impulse is simulated of the rectifier thyristors receives no pulses between 0.5 and 0.52 seconds, and one of the inverter thyristors receives the pulses between 1 and 0.02 seconds. Figure 11 the obtained DC voltage and current when using the DC/DC converter. The results are obtained by using the DC/DC converter.

The pulses of the DC/DC control system are sent to switches of the DC/DC converter. The function of the HVDC system is reestablished irrespective of the location of the missed pulses.

3.3 Results analysis and discussion

When the AC grid voltage increases by relatively small values (between 4% and 12%), the capacitors are gradually charged,until they reach a new DC voltage level. However, if the voltage increases considerably, the capacitors require a significant amount of the current to reach the DC voltage level. This high current which passes through the smoothing reactor causes a considerable voltage unlike the one generated by the AC/DC (or DC/AC) converter. As a result, a commutation failure occurs because one of the DC/AC switches is not switched on at the required time, leading to a short-circuit.

When an AC grid voltage is subjected to an acceptable voltage drop (between 4 and 8%), the capacitors discharge gradually, allowing them to reach a new DC voltage level that corresponds to the reduced AC grid voltage. However, in cases where the decrease is significant, the capacitors discharge through the smoothing reactors with high current values which generates a considerable coil voltage ($U_L = L\frac{di}{dt}$). Consequently, similarly to the previous scenario, due to commutation failure the DC voltage drops lead to a short-circuit.

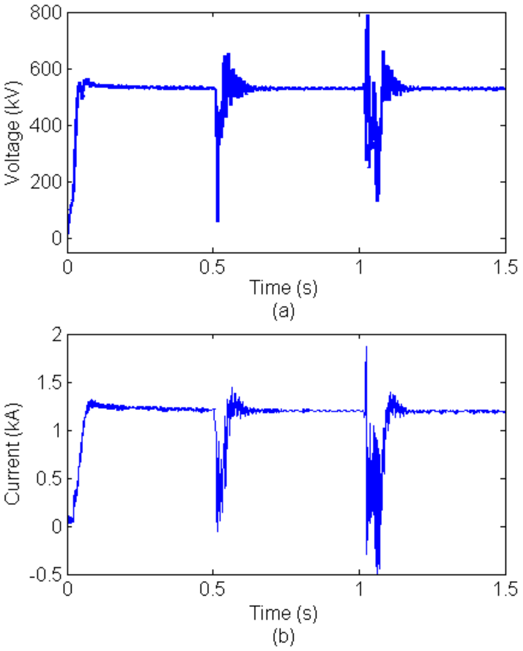


Figure 11. The parameters obtained with missing pulse:(a) DC voltage, (b) DC current.

When the impulse is missed in the rectifier, the smoothing reactor voltage may increase but without reaching the voltage applied by the rectifier. For the inverter, each thyristor must be followed by another one, and if not followed, a commutation failure occurs at the inverter side.

To solve the problems, some steps need to be taken of the LCC system, such as changing the pulse angles at the rectifier and inverter (which requires changing the reactive-power compensation), changing the AC voltages using on-load tap changers, etc. For these operations to be taken require a good communication needs to be established between the two HVDC poles. In the opposite case, the HVDC system may be badely affected.

The common issue of the commutation failures are the voltages of the smoothing reactors greater than the one applied by the rectifier. After the fault disappearance, the voltage applied by the rectifier should not be greater than the one of the smoothing reactors. To sum up, on the DC side, the smoothing reactor voltage is the prevailing factor to correctly maintain the HVDC function by keeping the reactor voltage lower than the one applied by the rectifier. So, to reestablish the HVDC link function, the supply of the smoothing reactors during faults must be interrupted and their voltage reduced values reestablished to enable the DC power coming from the rectifier to continue in the desired path.

Using our DC/DC converters, a change is observed in the behavior of the HVDC system when affected by to the above faults :

- The DC/DC converter interrupts the HVDC function during at a considerable variation in the AC grid voltage value and the DC voltage and current have to be maintained close to their nominal value with some oscillations. After removing the fault the load flow is reestablished and the HVDC connection is restored.
- At a missed For the impulse missing, the power supply is interrupted and reestablished after fault removal.

4 CONCLUSION

The paper presents a method for a monopolar HVDC system of the LCC technology when affected by voltage and control faults without needing any communication between the HVDC poles. To evaluate the HVDC system robustness, two faults have been considered and simulated with the CIGRE Benchmark HVDC system, i.e. AC voltage variations and missed impulses in the rectifier or the inverter. It is shown that the CIGRE system is not robust to the disturbances:

- AC grid voltage which is by some 10 % or more higher than the nominal voltage results in a commutation failure in the inverter.
- A missed pulse in the inverter causes a to commutation failure in this later.

At such faults, the smoothing reactor voltage increases above the one generated by the power converters, thus leading to a commutation failure and a short-circuit.

To reestablish the function of the HVDC system, the power supply needs to be disconnected from the rectifier and inverter. This requires a good communication between the HVDC poles. So, for the CIGRE Benchmark to function well, an autonomous system needs to be installed to dissipate the stored energy in the smoothing reactors and its voltage and to ensure that the power flow is maintained.

For this, a DC/DC converter of the buck configuration is proposed to be integrated in the DC filter. The DC/DC switch interrupts the DC grid current when the smoothing reactor voltage is higher than the nominal voltage, and the energy in the smoothing reactor is dissipated into the other elements of the DC filter through a freewheel diode. Using the DC/DC converter improves the CIGRE Benchmark stability at faults needing no AC/DC converter controllers and no communication between the HVDC poles. The power flow is disconnected during faults and the required value of the smoothing reactors voltage is maintained to reestablish of the HVDC system after a disturbance disappearence.

ACKNOWLEDGMENT

The authors would like to thank the ENSTI and the Cardiff School of Engineering for the collaboration.

REFERENCES

[1] H. Minxiao; A. Gole. Modeling and Simulation of HVDC Transmission. IET Digital Library. Energy Engineering, 2020. DOI: 10.1049/PBPO116E.

[2] J. Arrillaga. High Voltage Direct Current Transmission. IET Digital Library. Energy Engineering, 1998. DOI: 10.1049/PBPO029E.

[3] O. Ikotun; E.B. Agyekum; E.M. Ahmed; S. Kamel. Using Matlab/Simulink Software Package to Investigate Fault Behaviors in HVDC System. Mathematics 2022, 10, 3014. https://doi.org/10.3390/ math10163014

[4] S. Sarhan; A.M. Shaheen; R.A. El-Sehiemy; M. Gafar. Enhanced Teaching Learning-Based Algorithm for Fuel Costs and Losses Minimization in AC-DC Systems. Mathematics 2022, 10, 2337. https:// doi.org/10.3390/math10132337

[5] S. Lu; W. Lin; W. Yao; J. Wen. Control of two LCC-HVDC interconnected through DC-DC autotransformer. 12th IET International Conference on AC and DC Power Transmission (ACDC 2016), 2016, pp. 1-6. DOI: 10.1049/cp.2016.0438

[6] M. Langwasser; G. De Carne; M. Liserre ; M. Biskoping. Improved Fault Current Calculation Method for Pole-to-Pole Faults in MMC Multi-Terminal HVDC Grids Considering Control Dynamics. IEEE Energy Conversion Congress and Exposition (ECCE), 2018, pp. 5529-5535. DOI: 10.1109/ECCE.2018.8557979

[7] M. Langwasser; H. Imaneini; G. De Carne; M. Liserre .Estimation and Interruption of Short Circuit Currents in HVDC Systems. IEEE Power & Energy Society General Meeting (PESGM), 2019, pp. 1-5. DOI: 10.1109/PESGM40551.2019.8973517

[8] S. Wu; X. Zhang; W. Jia; Y. Zhu; L. Qi; X. Guo; X. Pan. A Modular Multilevel Converter With Integrated Energy Dissipation Equipment for Offshore Wind VSC-HVDC System. IEEE Transactions on Sustainable Energy, 2022 .vol. 13, no. 1, pp. 353-362. DOI: 10.1109/TSTE.2021.3111751

[9] M. Ahmad; Z. Wang; M. Shafique; M.H. Nadeem. Significance of fault-current-limiters and parameters optimization in HVDC circuit breakers for increased capacity of VSC-HVDC transmission networks application, Energy Reports 2022. Vol. 8., pp. 878-892. https://doi.org/10.1016/j.egyr.2021.12.024.

[10] S. Sun; S. Wang; Y. Sun; X. Yu; R. Yin; H. Hu; H. Ding; L. Li; L. Cao. Analysis of the Hybrid-MMC-HVDC Short-Circuit Current under MMC AC System Symmetrical Fault. 3rd Asia Energy and Electrical Engineering Symposium (AEEES), 2021, pp. 41-45. DOI: 10.1109/AEEES51875.2021.9403134

[11] J. A. Murillo; M. A. Rios.Analysis of DC Faults into Hybrid HVAC/HVDC Systems. IEEE 22nd Workshop on Control and Modelling of Power Electronics (COMPEL), 2021, pp. 1-5. DOI: 10.1109/COMPEL52922.2021.9645974

[12] Z. Zhou, ;Z. Chen, ;X. Wang, D. Du, ;G. Yang, ;Y. Wang, ;L. Hao. AC fault ride through control strategy on inverter side of hybrid HVDC transmission systems. J. Mod. Power Syst. Clean Energy. 2019, Vol. 7, pp. 1129–1141. https://doi.org/10.1016/j.ijepes.2021.107076

[13] S. M. Alagab; S. Tennakoon; C. Gould. Comparison of Single-stage and Multi-stage Marx DC-DC converters for HVDC application. 53rd International Universities Power Engineering Conference (UPEC), 2018, pp. 1-6. DOI: 10.1109/UPEC.2018.8541990

[14] S. Zhang; B. Li; X. Zhao; Y. Zhang; W. Wang ;D. Xu.A Transformerless Hybrid Modular Step-up DC/DC Converter for Bipolar and Symmetrical Monopolar HVDC Interconnection. 4th IEEE Workshop on the Electronic Grid (eGRID), 2019, pp. 1-6. DOI: 10.1109/eGRID48402.2019.9092730

[15] F. Qin; T. Hao; F. Gao; T. Xu; D. Niu; Z. Ma. A Multiport DC-DC Modular Multilevel Converter for HVDC Interconnection. IEEE Applied Power Electronics Conference and Exposition (APEC), 2020, pp. 520-524. DOI: 10.1109/APEC39645.2020.9124277

[16] G.J. Kish; M. Ranjram; P.W. Lehn. A Modular Multilevel DC/DC Converter With Fault Blocking Capability for HVDC Interconnects. IEEE Transactions on Power Electronics 2015, vol. 30, no. 1, pp. 148-162. DOI: 10.1109/TPEL.2013.2295967.

[17] J. D. Páez, ; D. Frey, ;J. Maneiro ; S. Bacha;P. Dworakowski. Overview of DC–DC Converters Dedicated to HVdc Grids. IEEE Transactions on Power Delivery 2019. vol. 34, no. 1, pp. 119-128. DOI: 10.1109/TPWRD.2018.2846408

[18] The CIGRE HVDC BENCHMARK MODEL - A NEW PROPOSAL WITH REVISED PARAMETERS. Working group 14.02 (Control in HVDC Systems) of study committee 14. ELECTRA. December 1994.

[19] M. H. RASHID. POWER ELECTRONICS HANDBOOK. Fourth Edition. Butterworth-Heinemann, 2018. https://doi.org/10.1016/B978-0-12-811407-0.09995-5..

Sofiane Chiheb received his M.S. degree from the Badji Mokhtar University of Annaba, in 2013 and his Ph. D. degree in electrical engineering from the École Nationale Polytechnique (ENP), in 2018. He is currently an assistant professor with the Ecole Nationale Supérieure de Technologie et d' Ingénierie (ENSTI) Annaba - Algeria. His research interests include high-voltage techniques, grounding systems, power grids and renewable energies.

Badri Rekik received his B.E., Magister and Ph. D. degrees in Electrical Engineering from the Badji Mokhtar University of Annaba, Algeria. Currently, he is with the Ecole Nationale Supérieure de Technologie et d'Ingénierie (ENSTI) Annaba - Algeria. His research interests include power transformers, power grids and renewable energies.

Tarek Messikh received his B.E. degree in Electrical Engineering from the Badji Mokhtar University of Annaba, Algeria and his Master & Ph.D degree of Electrical Engineering from University of Malaya, Malaysia. Currently he is an assistant professor with the Ecole Nationale Supérieure de Technologie et d' Ingénierie (ENSTI) Annaba - Algeria. His research interests include power electronics and power system studies.

Omar Kherif received his M.Eng. and Ph.D. degrees in electrical engineering from the École Nationale Polytechnique (ENP), in 2015 and 2019, respectively. From 2016 to 2018, he was a Mathematical-Analysis Assistant Teacher with ENP. He was also a Volunteer Researcher with the Laboratoire de Recherche en Electrotechnique, ENP where he co-supervised several master's theses. Currently he is a KTP Associate with the Cardiff University. His research interests include high-voltage techniques, electromagnetic transients, and earthing and power system protection.