Steady-state and transient performance of HVDC link based 3-level VSC supplying a passive load

Performances en régime stationnaire et transitoire de la liaison CCHT utilisant le VSC 3 niveaux alimentant une charge passive

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ملخص

هذا المقال يناقش الحالة الساكنة والأداء الديناميكي للنظام نقل التيار الكهربائي المستمر ذي التوتر العالي الموصول بشبكة خاملة، نظام نقل التيار المستمر العالي التوتر المعتمد على المحول ذو مصدر التوتر يوظف تقنية تعديل عرض الذبذبات وبهذا يمثل الجهاز الأمثل لنظام النقل المرن للتيار المتناوب. بجانب التحكم في تدفق الطاقة الكهربائية بإمكانه إمداد طاقة رد الفعل ويوفر تحكم ديناميكي مستقل عند حديه. نظام التحكم في المحولين ذو ثلاث مستويات تم مناقشته، هذه الدراسة تحوي تحليل قدرة الطاقة النشطة وطاقة رد الفعل بجانب تدفق الطاقة، تمت مراقبة الأداء الديناميكي بعد حوادث خارجية في الجهاز. أخيرا النموذج والنتائج تم عرضها وتجريبها باستعمال المحاكاة ببرنامج مطلب سيملينك وصندوق الأدوات الخاص به سيمباور سيستم.

الكلمات المفتاحية: نظام نقل التيار المستمر ذي التوتر العالي، ترانزستور ثنائي القطب معزول المدرأة، تعديل عرض الذبذبات الجيبية، آلية التحكم، حمولة خاملة.

Résumé

Cet article étudie le fonctionnement en régime permanent et transitoire (HVDC) de réseaux de transport à courant continu à haute tension connectés à un réseau passif. Le CCHT à base d'IGBT utilisant la MLI représente bien les systèmes FACTS. En plus de contrôler le transit de puissance, il peut fournir de la puissance réactive et offrir un contrôle dynamique indépendant au niveau de ses deux terminaux. Les systèmes de contrôle pour le redresseur et l'onduleur sont examinés. Les réseaux de transport sont équipés par des convertisseurs à trois niveaux à base de source de tension. Cette étude comprend l'analyse, le transit de puissance active ainsi que les performances dynamiques suite aux défauts AC externes. Enfin, les modèles et les résultats sprésentés sont testés par des simulations à l'aide de Matlab Simulink et SimPowerSystems toolbox.

Mots clé : *CCHT- convertisseur à base de source de tension- MLI - technique de contrôle - charge passive.*

Abstract

This paper investigates the steady-state and transient performance of high-voltage DC (HVDC) transmission systems connected to passive network. The VSC HVDC tie employing PWM may well represent the ultimate FACTS device. Besides controlling the through power flow, it can supply reactive power and provide independent dynamic control at its two terminals. The control systems for rectifier and inverter are discussed in DC (HVDC) transmission systems based on three-level voltage source converters. The study involves analysis of active-reactive power capabilities (P-Q envelope) including active power flow and provision of voltage support to AC networks. The transient performance is explored by examining the VSC_HVDC response to external AC faults. Finally, the models and results are presented and tested by simulations using Matlab Simulink and its toolbox SimPowerSystems.

Keywords : *HVDC- voltage source converter (VSC) - IGBT- SPWM- Control design - passive load*

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1. INTRODUCTION

With the scale of the new energy utilization enlarging, and the power requirements of offshore drilling platforms, isolated island, and other passive load, the traditional ac/dc transmission technology becomes diseconomical and environmental pollution.

VSC-HVDC system is a new generation of HVDC technology based on pulse width modulation and voltage source converter (VSC), the modern high-power power electronic technology applied in the power system. Comparing with traditional HVDC based on phase control converter (PCC), control method of VSC-HVDC system is flexible, and has no failure of commutation, small harmonic content, without capacity requirements about terminal power system, the reactive power of system could be controlled. The economic capacity of VSC-HVDC system extends from several megawatts to hundreds of megawatts [1,2,3]. There are seven VSCHVDC system put into operation abroad [4,5].

The introduction of pulse width modulated voltage source converter technology into high-voltage DC (HVDC) transmission systems has increased their viability in many applications in terms of cost and performance [6]. The main benefits of VSC-HVDC over the classic LCC-HVDC are [2,7,8] :

- Converter inherent reactive power capability (resulting in smaller converter size and reduced filtering requirements.
- Independent control of active and reactive power (allowing the converters to provide damping, frequency and voltage support to AC networks without compromising system performance).
- Black start capability (extending the use of HVDC systems for connection of weak AC networks with no generation).
- Power reversal is achieved instantaneously and without the need to reverse the DC link voltage polarity. This allows the use of inexpensive cable and transformers with lower insulation requirements, as they are not required to withstand high voltage stresses during power reversal.
- Fault ride-through capability, improves transient stability of the ac networks.

The objective of this paper is to study the operational performance of VSC_HVDC supplying power to passive network and its control strategies. The vector control method is studied using 3-level VSC connected to an active AC system at the first end & passive load at the second end of the HVDC link. Finally, simulations and results are presented by means of Matlab Toolbox Simpower System. Compared to previous studies [6,7,9], this paper focuses on the controller performance in the operation range against some steps change in the load and shows the control of active and reactive power. Following that typical operating contingency scenarios are simulated in order to evaluate transient performance. The simulation results confirm that the control strategy has fast response and strong stability.

2. VSC-HVDC TRANSMISSION MODEL

2.1 Basic principle

The HVDC system is modeled as a conventional bi-polar transmission system. Two series connected DC capacitors of same size are employed across the DC transmission line with grounded midpoint for VSC operation, to reduce the ripples in DC voltage. A smoothing reactor is also connected in series with transmission line for reducing the ripple in DC current. During failure or scheduled maintenance of one pole of transmission line, a reduced amount of power can still be transmitted by other pole.

2.2 Fundamental Of VSC-HVDC Transmission

The fundamentals of VSC transmission operation may be explained by considering the terminal as a voltage source connected to the AC transmission network via a three-phase reactor. Changing the fundamental frequency voltage phase angle across the series reactor controls the power; whereas, changing the fundamental frequency voltage magnitude across the series reactor controls the reactive power. The main circuit structure of VSC-HVDC transmission system supplying power to passive network is shown in figure 1 [2,7,10,11].

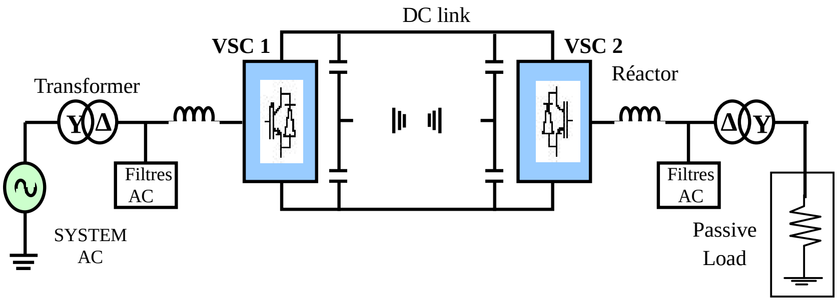


Figure 1: Basic VSC-HVD transmission supplying a Passive Load

Figure 2 shows a phasor diagram for the VSC converter connected to an AC network via a transformer inductance. The fundamental voltage on the valve side of the converter transformer, i.e. UV (1), is proportional to the DC voltage has been expressed in equation (1):

$$U_{V(1)} = k_u \cdot U_d \qquad (1)$$

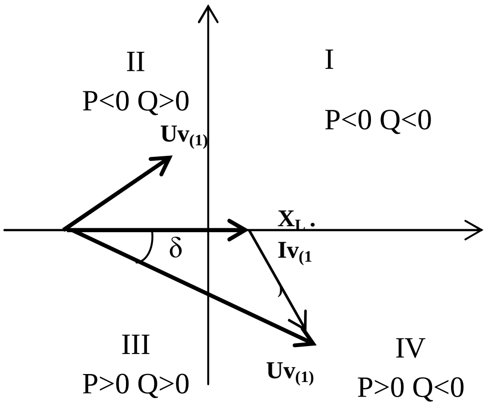


Figure 2: Phasor diagram of VSC and direction of power flows

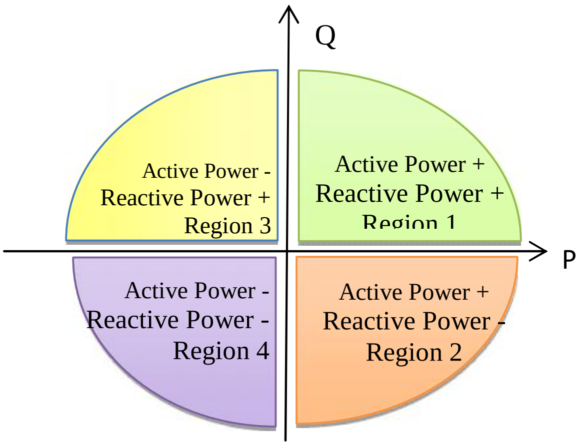
The quantity k_u can be controlled by applying additional number of commutation per cycle, i.e. applying pulse with modulation (PWM). Using the definition of the apparent power and neglecting the resistance of the transformer results in the following equations for the active and reactive power:

$$P = U_d \cdot I_d = \frac{U_L \cdot U_{V(1)}}{X_L} \sin ¢ \qquad (2)$$

$$Q = \frac{U_L \cdot (U_L - U_{V(1)} \cdot \cos ¢)}{X_L} \qquad (3)$$

The active power and reactive power exchanged by VSC-HVDC and AC system can be adjusted promptly by change the magnitude and angle of the output AC voltage of the VSC-HVDC. This characteristic of VSC-HVDC (Fig.3) makes itself more flexible than other FACTS technology, such as SVC, STATCOM, also than traditional HVDC. By means of Phase Width Modulation (PWM) technology, especially Sinusoidal PWM (SPWM), two degrees of freedom, i.e. phase and amplitude can be acquired. Phase and Amplitude Control (PAC) technology is developed for VSC-HVDC applications [10,12]. The VSC can easily interchange active and reactive power with an AC network as well as a synchronous machine.

But the extent of the active power and reactive power which can be adjusted in VSC-HVDC is subject to the rate power limit and the operation condition of the time. The adjusting ability of the active power and that of the reactive power influence each other dynamically. So it is necessarily to analyze the ability in real time. Figure 3 shows a typical P-Q diagram for a VSC based transmission system expressed in per unit [1,13].



Green = active power delivery and reactive power delivery
Orange = active power delivery and reactive power receipt
Yellow = active power receipt and reactive power delivery
Magenta = active power receipt and reactive power receipt

Figure 3 : P-Q characteristics of a VSC-HVDC system

$$P^2 + \left(Q - \frac{U_L^2}{X_L}\right)^2 = \left(\frac{U_L \cdot U_{V(1)}}{X_L}\right)^2 \qquad (4)$$

If the output voltage of the converter UV (1) is reduced, e.i by using PWM, supply of any active and reactive power within the circle is possible.

3. CONTROL STRATEGY

Generally the control strategy of a two terminal VSC-HVDC transmission line is to keep one terminal DC voltage constant as operation point, and adjust the other terminal DC current or active power order. The AC voltage or the reactive power of the two terminals can be controlled.

Figure 4 shows an overview diagram of the VSC control system and its interface with the main circuit [9,10,14]. The converter 1 and converter 2 controller designs are identical. The two controllers are independent with no communication between them. Each converter has two degrees of freedom. In our case, these are used to control:

I. P and Q in station 1 (rectifier)

II. Ud and Q in station 2 (inverter).

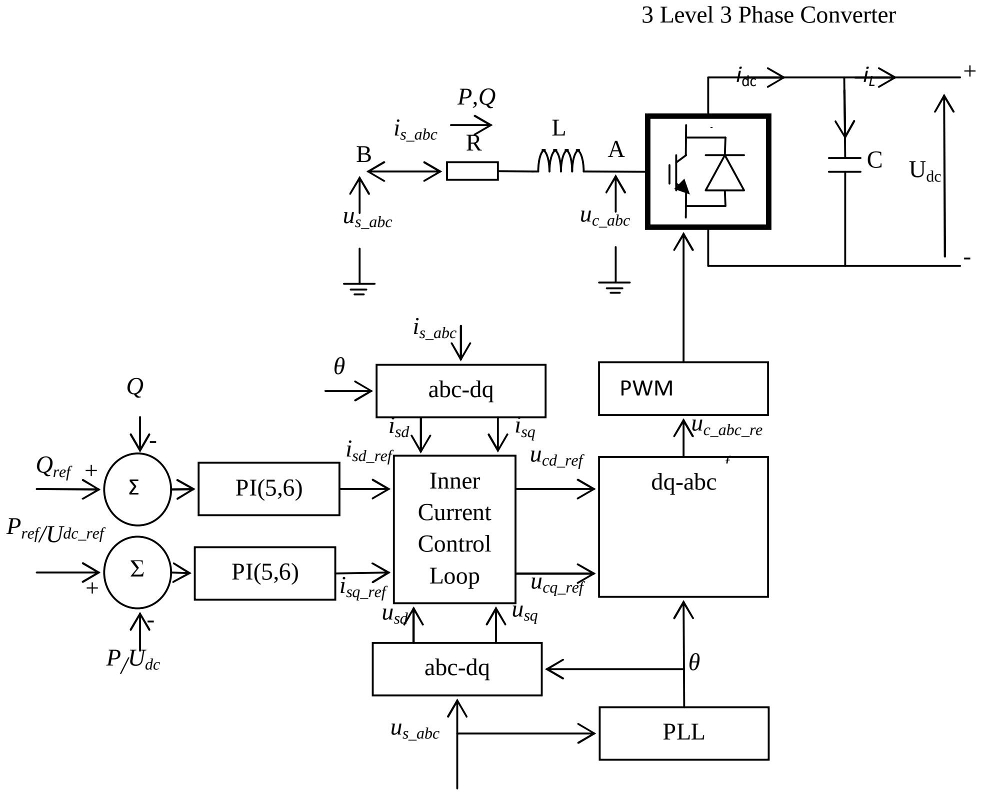


Figure 4: Overview diagram of the VSC control system

3.1. Phase locked loop

The phase locked loop (PLL) shown in figure 5 is used to synchronize the converter control with the line voltage and also to compute the transformation angle used in the d-q transformation. The PLL block measures the system frequency and provides the phase synchronous angle ϴ for the d-q transformations block. In steady state, sin (ϴ) is in phase with the fundamental (positive sequence) of the α component and phase A of the point of common coupling voltage (Uabc).

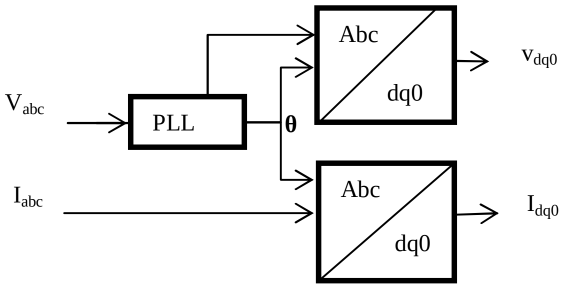


Figure 5: Phase locked loop block

3.2. Outer active and reactive power and voltage loop

The active power or the DC voltage is controlled by the control of δ and the reactive power is controlled by the control of the modulation index (m). The instantaneous real and imaginary power of the inverter on the valve side can be expressed in terms of the dq component of the current and the voltage on the valve side as follows:

$$p = \frac{3}{2} \cdot \mathrm{Re}(\bar{u}_f^{dq} \cdot \bar{i}_v^{*dq}) = \frac{3}{2} \cdot (u_{fd} \cdot i_{vd} + u_{fq} \cdot i_{vq}) \quad (5)$$

$$q = \frac{3}{2} \cdot \mathrm{Im}(\bar{u}_f^{dq} \cdot \bar{i}_v^{*dq}) = \frac{3}{2} \cdot (-u_{fd} \cdot i_{vq} + u_{fq} \cdot i_{vd}) \quad (6)$$

If the reference of the dq-frame is selected such that the quadrature component of the voltage is being very small and negligible (uLq ≈ 0) then the equations (5) and (6) indicate that the active and the reactive power are proportional to the d and q component of the current respectively. Accordingly, it is possible to control the active power (or the DC voltage or the DC current) and the reactive power (or the AC bus voltage) by control of the current components ivd and ivq respectively. The active and reactive power and voltage loop contains the outer loop regulators that calculate the reference value of the converter current vector (I*dq) which is the input to the inner current loop [15].

3.3. Inner current loop

The AC Current Control block tracks the current reference vector ("d" and "q" components) with a feed forward scheme to achieve a fast control of the current at load changes and disturbances (e.g., so short-circuit faults do not exceed the references) [3,6,13,14]. In essence, it consist of knowing the U_dq vector voltages and computing what the converter voltages have to be, by adding the voltage drops due to the currents across the impedance between the U and the PWM-VSC voltages. The state equations representing the dynamics of the VSC currents are used (an approximation is made by neglecting the AC filters). The "d" and "q" components are decoupled to obtain two independent first-order plant models. A proportional integral (PI) feedback of the converter current is used to reduce the error to zero in steady state. The output of the AC Current Control block is the unlimited reference voltage vector Vref_dq_tmp.

3.4. DC voltage balance control

The difference between the DC side voltages (positive and negative) are controlled to keep the DC side of the three level bridge balanced (i.e., equal pole voltages) in steady-state. Small deviations between the pole voltages may occur at changes of active/reactive converter current or due to nonlinearity on lack of precision in the execution of the pulse width modulated bridge voltage. Furthermore, deviations between the pole voltages may be due to inherent unbalance in the circuit components impedance [9].

4. MODEL PERFORMANCE ANALYSIS

The dynamic performance of the transmission system is verified by simulating the:

A. VSC_HVDC response to external AC fault at the rectifier side (source).

B. VSC_HVDC response to external AC faults at the inverter side (load) & the dc line.

4.1. Case 1

A single phase to ground fault was first applied at t = 2.8s during 0.1s (5 cycles) at station 1 (Fig. 6) AC bus in order to investigate the behavior of VSC-HVDC during unbalanced faults. Figure 7 presents the simulations results. From the simulation, it can be noted that before a single phase to ground fault at station 1, the active power flow is kept constant, transmitted from converter 1 to converter 2.

These fault cause transients on the active and reactive power. However, the DC voltage and the active & reactive powers P2 and Q2 at VSC 2 don't change.

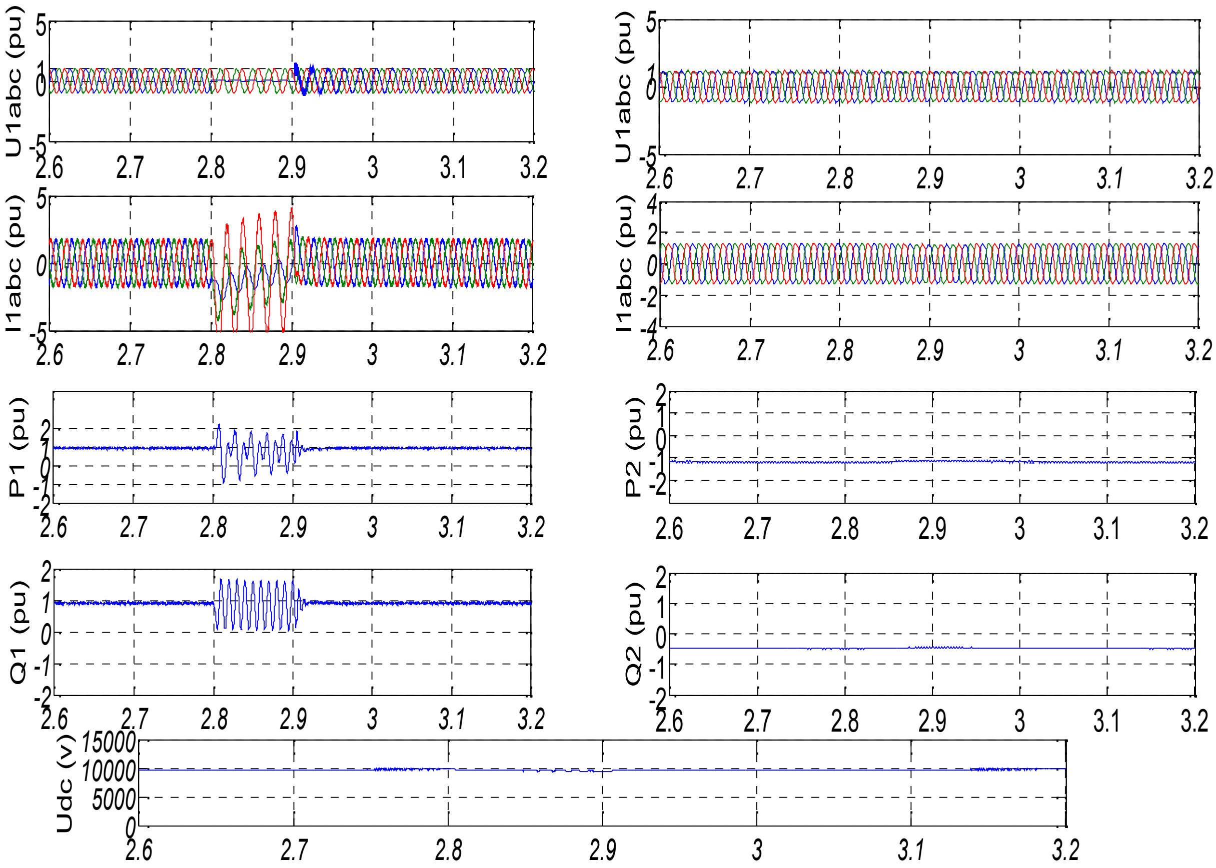


Figure 6: AC side perturbations at the rectifier side (source)

4.2. Case 2

A single phase to ground fault was first applied at t = 1.2s during 0.1s (5 cycles) at station 2 (Fig. 7) AC bus in order to investigate the behavior of VSC-HVDC during unbalanced faults. A second perturbation follows. A fault to ground is applied at the dc line (Fig. 7) at t = 2.1 s and is cleared at 5 cycles after the fault, i.e., at t = 2.2 s. Figure 7 presents the simulations results. From the simulation, it can be noted that before a single phase to ground fault at station 2, the active power flow is kept constant, transmitted from converter 1 to converter 2, and is kept constant during the fault.

The DC voltage drops and it contains an oscillation during the fault. Consequently the transferred DC power contains also the oscillation. During the station 1 side fault the transmitted power can be kept constant except a small oscillation during the fault. All oscillations in voltages and currents at both systems, means that the phase voltages and currents at both systems are unbalanced. Note that during the three-phase fault, the transmitted DC power is almost zero. At this moment the two VSC stations can be considered as independent STATCOM. The system recovers well after the fault within 50 ms.

During the severe single phase to ground fault at station 2 at t = 2.1s, the DC voltage is decreased to 0.7 pu during the fault and recovers fast and successfully to 1.0 pu voltage after clearing the fault. The transmitted power flow is reduced to low value during the fault and recovers after the fault. It takes about 50 ms to recover the steady state before the next perturbation initiation.The DC voltage which can be controlled to 1.0 pu during the fault, has some oscillations at the beginning of the fault and at clearing the fault.

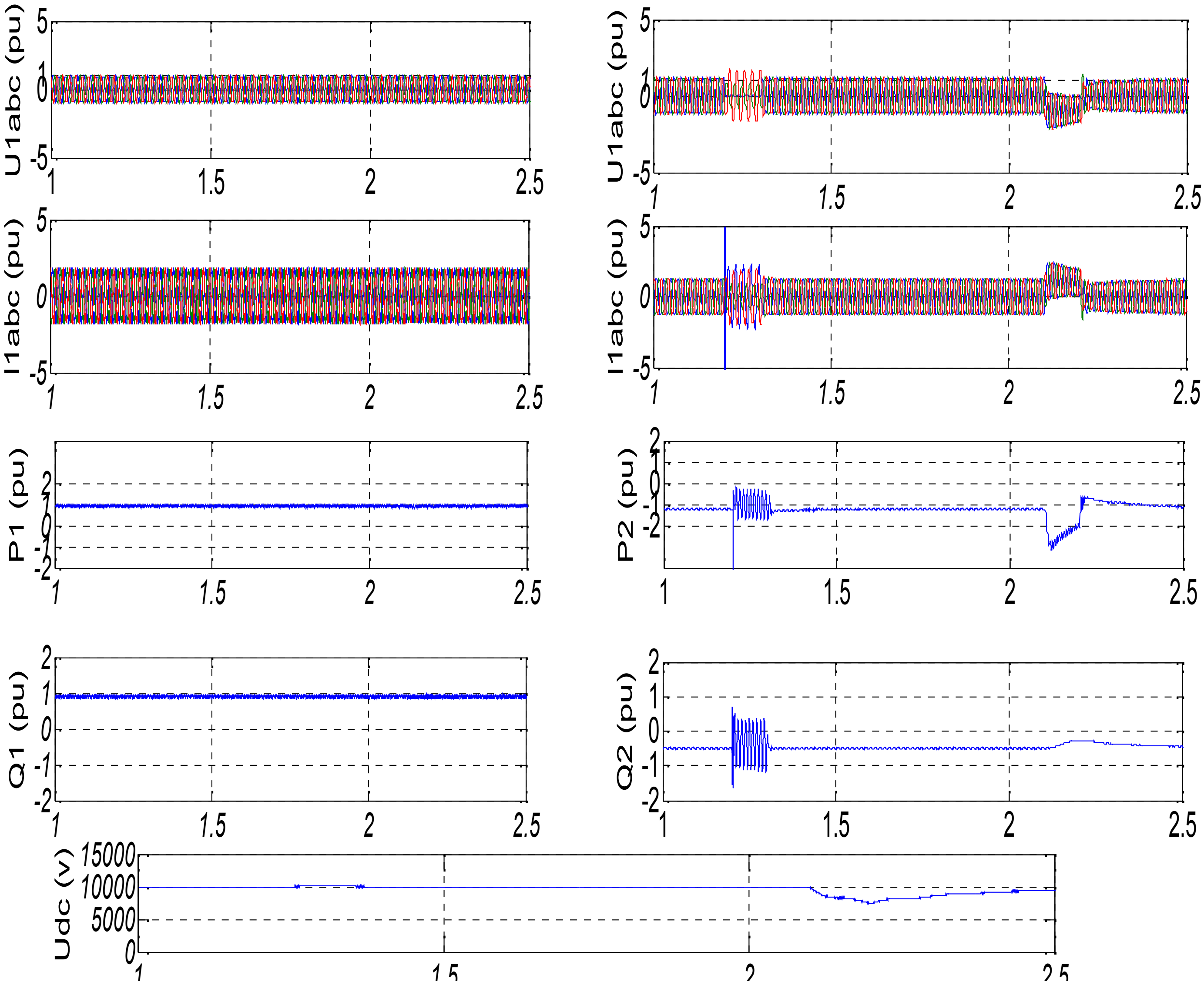


Figure 7: AC side perturbations at the rectifier side (load) & DC line.

5. CONCLUSION

In this paper, we have presented the steady-state and dynamic performances of VSC_HVDC transmission system supplying power to passive network during unbalanced faults. In all cases the proposed control strategy has been shown to provide fast and satisfactory dynamic responses of the proposed system. From the simulation, it can be obtained that the VSC-HVDC can fulfill fast and flexible power transfers. It can be obtained also that during a single-phase fault the transmitted power can be kept constant except a small oscillation during the fault.

The system advantages of deploying a VSC HVDC transmission system Tie with standby dynamic voltage control during network contingencies with it VSC-HVDC technology can make passive network voltage more stably, and have the same affection as the STATCOM, in a certain extent; it improves the system voltage stable.

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Nomenclature

¢ = phase shift between U_L and $U_{V\,(1)}$

µ = source voltage angular frequency

C = DC side capacitance

d, q = synchronous d -q axis

I_V = source current

L, R = phase reactor inductance and resistance

p, n = positive, negative components

P, Q = AC active, reactive power inputs

ref = reference value for controller

U_d, I_d, P_d = DC side voltage, current, power

U_f = AC voltage in the AC network at the filter-bus

U_L = the sinusoidal AC voltage in the AC network

$U_{V\,(1)}$ = the fundamental line to line voltage (valve side)

X_L = the leakage reactance of the transformer

α, β = stationary α -β axi

Appendix

Station 1(Rectifier side)	110kV(80°), 2000 MVA, *SCR* = 10, L_1 = 31.02 mH, R = 0.003Ω, L_2 = 33.6 mH. f = 50 Hz
Station 2(Passive load)	10kV(80°),P= 20 MW, Q_L= 12.5 MVAR , f = 50Hz
Transformer	Yg/Δ, 110kV/10kV, 200 MVA, 15%
Main DC capacitor	70 µF
DC Cables	50 Km×2 (R=0.015Ω/km, L = 0.792 mH/km, C = 14.4 µF/km
Switching frequency	1350 Hz