Eng. & Tech. Journal ,Vol.32, Part (A), No.7, 2014

HVDC Transmission Systems based Multi-level Voltage Source Converters for Iraqi Super Grid

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Received on: 10/10/2013 & Accepted on: 6/3/2014

ABSTRACT

High Voltage Direct Current Transmission (HVDC) with Voltage Source Converter (VSC) technology provides substantial technical and economical advantages for different applications compared to conventional HVDC transmission systems based on thyristor technology. This paper is focusing on the modeling and analysis of Three-Level Neutral Point Clamped (NPC-VSC) as it is one type of multi-level voltage source converter Diode-Clamped Circuit (DCC).This system is regard as light system based on HVDC transmission, of high power ratings (up to 600 MW). Application of the proposed technique is adopted and tested for Iraqi Super High Voltage Grid (400 kV), where the proposed model is simulated using MATLAB. The results show a good response of the control system for certain fault conditions considered to show the advantage of using such system.

Keywords: HVDC, Voltage source converter (VSC), IGBT, SPWM, Control design.

منظومه نقل التيار المستمر ذو الفولتية العالية بتقنيه محول مصدر الفولتية متعدد المستويات لشبكه الضغط الفائق العراقية

الخلاصة

توفر منظومه نقل التيار المستمر ذو الفولتية العالية (HVDC) مع تقنيه محول مصدر الفولتية (VSC) مزايا فنية واقتصادية كبيرة لمختلف التطبيقات بالمقارنة مع أنظمة نقل HVDC التقليدية القائمة على تكنولوجيا الثايرستور. يركز هذا البحث على نمذجة وتحليل محول مصدر الفولتية ذو الثلاث مستويات و النقطة الجامعة (NPC-VSC) كنوع من محولات مصدر الفولتية متعددة المستويات ذو الدايود الجامع (DCC). يعد هذا النظام كنظام فعال مع منظومه نقل التيار المستمر ذو الفولتية العالية (HVDC), لأنظمه القدرة العالية التي تصل ال (600 ميغاواط). تم اعتماد تطبيق هذه التقنية المقترحة واختبارها للشبكة الوطنية العراقية ذات الضغط الفائق (400 kV)،

حيث تم محاكاه النموذج المقترح باستخدام MATLAB. تظهر النتائج وجود استجابة جيدة من قبل نظام السيطرة لبعض حالات الخطأ لإظهار واثبات استخدام مثل هذا النظام في التطبيقات.

INTRODUCTION

An increasing necessity around the world for transmitting huge energy quantities through long distances has pushed the development of a new technology based upon power electronics systems. The new technology is the transmission of energy using High Voltage Direct Current (HVDC). The power electronic systems used different types of converters whose main component is a highly efficient switching device. Electronic devices began to show real prospects for high voltage direct current (HVDC) transmission, because of the ability of these devices for rectification and inversion. From early 1950's to 1975, the developments of HVDC transmission were sustained by converters having mercury arc valves. The next 25 years were sustained by line-commutated converters (LCC) using thyristor valves, also known as Current Source Converters (CSC). It is predicted that the next 25 years will be dominated by force-commutated converters known as Voltage Source Converters (VSC) [1]. This concept is based on high switching frequency components, such as IGBTs, and the use of pulse width modulation technology, which makes the possible to control active and reactive power flow separately. In 1997 the world's first HVDC Light test transmission was a 3MW ±10kV link was built in central Sweden [2], and the first commercial HVDC Light (50MW) commissioned in 1999, in Gothl and, Sweden. The VSC is feasible to transmit up to 600 MW with the equipment built today [3].

Light HVDC system

Figure (1) shows a representation of a typical VSC HVDC system [4]. The AC grid is connected to the converter through a transformer, a shunt connected filter and a phase reactor. All are three-phase elements, but are shown by their single-line representation. On the DC side, the DC capacitors and the conductors are shown. The major power components are:

1. Converter Transformers.
2. High voltage DC circuit.
3. Voltage Source Converters (VSC).

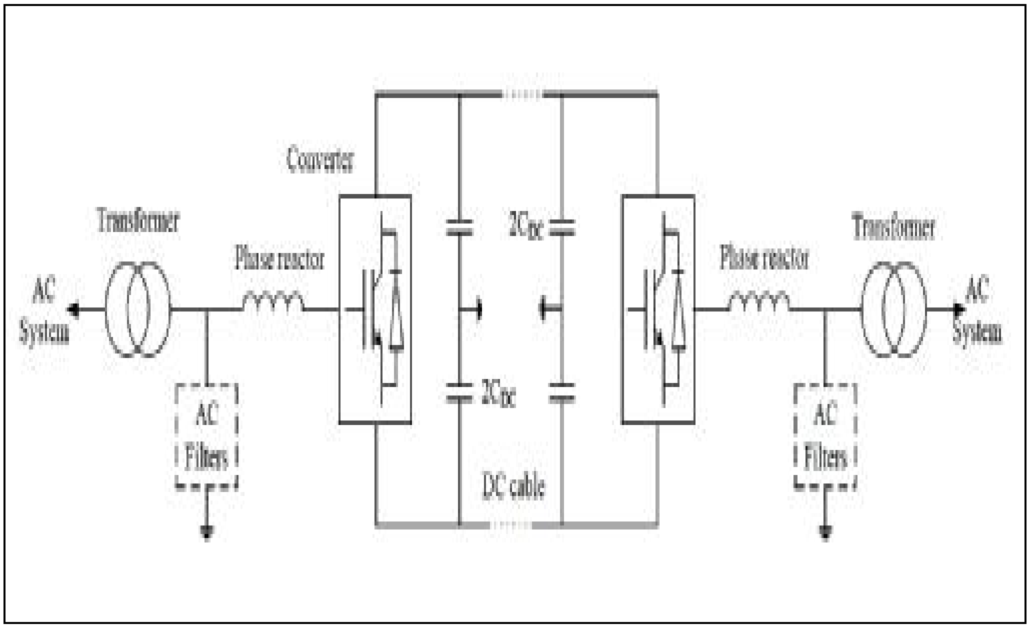

Figure (1): Typical VSC-HVDC system.

The system shown in Figure (1) is of bipolar type. One station comprises two equally designed VSCs, each providing a DC voltage Vdc.

Converter Transformers

Normally, the converters are connected to the AC system via transformers. The most important functions of the transformers are [5]:

1. To provide a reactance between converter terminals and AC system.
2. To transform the voltage of the AC system to a value optimized to the converter voltages and currents.
3. To connect two single 6pulse converters to form a 12pulse group.
4. To connect two single converters with different DC potentials to ground.

High Voltage DC Circuit

The DC circuit is formed by the storage capacitors and the DC cable or overhead line. A storage capacitor provides the corresponding VSC with a smooth DC voltage of a fixed polarity. To achieve maximum use of the power semiconductors of the VSC, the capacitor needs to be connected to the converter by a low inductive path. The size of the capacity is chosen according to the maximum DC voltage ripple tolerated [4].

A Light HVDC system instead cannot change voltage polarity. Power reversal is achieved by changing the direction of DC current. This allows to use new extruded DC cables, which are an attractive alternative to self-contained oil filled or mass impregnated paper insulated cables as used for conventional thyristor based HVDC systems.

The cable length is not limited as it would be in case of AC transmission systems. A major concern with AC cable transmission is balancing the reactive power demand of the cable, which is due to the large working capacitance. A Light HVDC transmission is therefore an alternative to long AC cable transmission.

Voltage Source Converter (VSC)

In general, converters might be divided into two groups that are to be distinguished by their operation principle. One group needs an AC system to operate. The AC system voltage forces the current to commutate from one phase to another. Using controlled semiconductors like thyristors, the point-on-wave for commutation can be chosen and thus, the power exchanged between AC and DC system via the converter can be controlled. Converters that rely on an AC system to operate are called Line Commutated Converters (CSC). Conventional HVDC systems employ Line Commutated Converters.

The second group of converters does not need an AC system to operate and is therefore called Self Commutated Converters (VSC). Depending on the design of the DC circuit, these groups can further be divided into Current Source Converters (CSC) and Voltage Sourced Converters (VSC). A CSC operates with a smooth DC current provided by a reactor, while a VSC operates with a smooth DC voltage provided by the storage capacitor.

Figure (2) shows an equivalent diagram of a Two-Level VSC as to be used for Light HVDC transmission systems. It consists of a 6pulse bridge equipped with IGBTs and an anti-parallel connected 6pulse bridge equipped with freewheeling diodes. Basically, either GTOs or IGBTs can be used as semiconductor switches. To achieve the required power rating, a number of devices are connected in series. GTO valves allow higher currents but less DC voltage than IGBT valves [6].

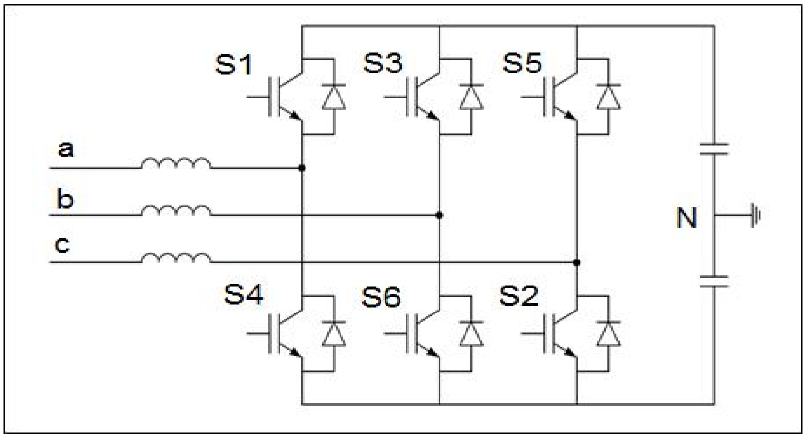

Figure (2): Two-level VSC.

For HVDC long distance transmission systems, high transmission voltages are advantageous to keep transmission losses low. This favors the use of IGBT valves.

Due to a switching frequency, that is considerably higher than the AC system power frequency, the wave shape of the converter AC current will be controlled to be very sinusoidal. This is achieved by special Pulse Width Modulation (PWM) methods.

Besides the 2level converter, 3level converters have been used for high power applications. Figure (3) shows an equivalent circuit of such a converter with neutral-point clamped voltage source converter [7].

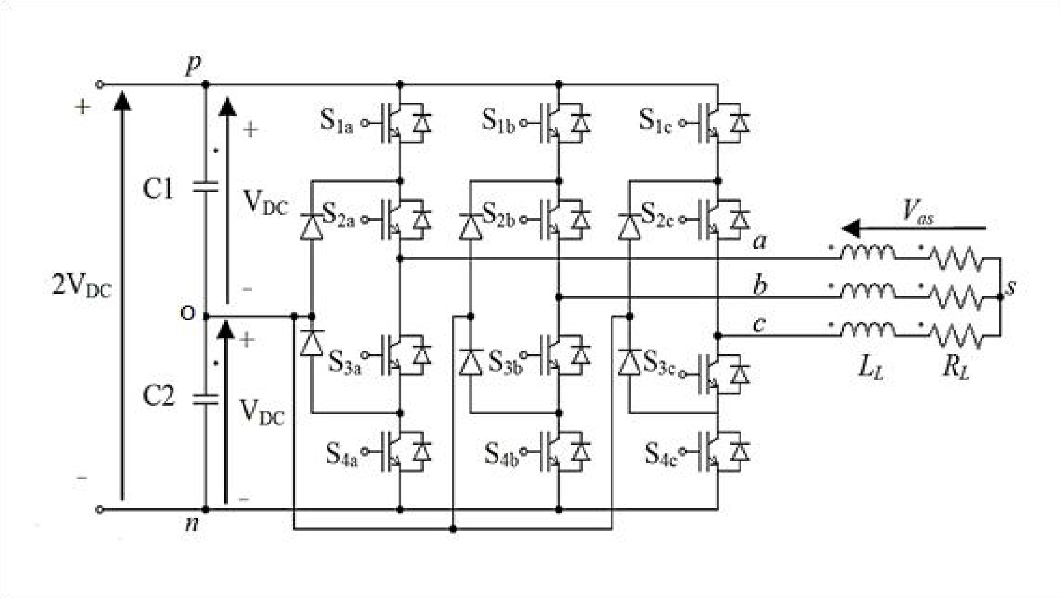

Figure (3): The schematic diagram of a conventional three-level neutral-point-clamped voltage source inverter using the IGBT switches [7].

Three Level Neutral Point Clamped (NPC-VSC)

Consider Figure (3) the NPC-VSC is supplied by two series-connected capacitors (C1 and C2), where both capacitors are charged to an equal potential of Vdc, with the DC-link middle point ‘o’ as a zero DC voltage neutral point. Each phase leg of the NPC-VSC consists of four series-connected switching devices and two clamping diodes. These diodes clamp the middle switches potential to the DC-link point ‘o’ [8].

In order to generate the three-level output, the switching devices in each phase leg are controlled according to the switching combinations presented in Table (1). At any time, only two of the four switching devices are turned on and the output terminal can be connected to any of the DC-link points (p, o or n), which can be represented by a switching state (P, O or N); for example switching state P represents the connection of the output terminal to the DC-link point ‘p’. Using the DC-link middle point ‘o’ as a reference, the NPC VSC is obviously able to generate three distinct voltage levels at the output terminal of each phase leg, Vxo, which can be determined using the following equation [8]:

$$V_{xo} = V_{Dc}(m_{x1} - m_{x3}) \qquad \dots\dots\dots (1)$$

The variables m_{x1} and m_{x3} represent the switch combinations (S1x & S2x) and (S3x & S4x) in each phase leg (x ∈{a, b, c}), which is one when both switches in the combination are ‘on’ and zero otherwise.

For a three-level three-phase NPC VSC, there are twenty-seven switching states that represent the connections of the output terminals (a, b and c) to their respective DC-link points. Having a star-connected load applied to the NPC VSC, as shown in Figure (3), these switching states are able to generate specific output phase (line-to-load neutral, s) and output line-to-line voltages. The output voltages can be determined using the following equations [8]:

$$\left.\begin{aligned} V_{as} &= (2/3).V_{Dc}[m_{a1} - m_{a3} - (1/2)(m_{b1} - m_{b3} + m_{c1} - m_{c3}] \\ V_{bs} &= (2/3).V_{Dc}[m_{b1} - m_{b3} - (1/2)(m_{a1} - m_{a3} + m_{c1} - m_{c3}] \\ V_{cs} &= (2/3).V_{Dc}[m_{c1} - m_{c3} - (1/2)(m_{a1} - m_{a3} + m_{b1} - m_{b3}] \end{aligned}\right\} \quad \ldots\ldots\ldots(2)$$

$$\left.\begin{aligned} V_{ab} &= V_{ao} - V_{bo} = V_{Dc}(m_{a1} - m_{a3} - m_{b1} + m_{b3}) \\ V_{bc} &= V_{bo} - V_{co} = V_{Dc}(m_{b1} - m_{b3} - m_{c1} + m_{c3}) \\ V_{ca} &= V_{co} - V_{ao} = V_{Dc}(m_{c1} - m_{c3} - m_{a1} + m_{a3}) \end{aligned}\right\} \quad \ldots\ldots\ldots(3)$$

With the ability to generate three voltage levels at each output terminal, the NPC VSC is able to produce five distinctive levels (±2VDC, ±VDC and 0V) for the output line-to-line voltages. Compared to the two-level voltage source converter, the NPC VSC has the following advantages:

- By constructing the output waveforms with multiple voltage levels (e.g. five levels for the output line-to-line voltage), the output waveform approches the desired sinusoidal waveform so the harmonic distortion is lower.
- By having the output consists of multiple smaller voltage levels with lower ΔV, the stresses imposed on motor bearing and winding isolation in the adjustable speed drive application are lower than that for a two-level voltage source converter.
- The connection of the clamping diodes limits the voltage stress across the off state switching devices to one capacitor voltage level; half of the DC-link. Due to the reduced voltage stress, medium voltage rated semiconductor devices can be used to construct the converters for high voltage, high power applications voltage.

Control system of VSC-HVDC

Different control strategies are found in literature for the control of VSC-HVDC. Direct control and vector control methods which are based on voltage controlled VSC and current controlled VSC schemes respectively are the most widely used methods [9]. The current-controlled VSC offers potential advantages over the voltage-controlled VSC. The mains advantages being:

1) Better power quality as the current-controller converter is less affected by grid harmonics and disturbances.
2) Decoupled control of active and reactive power.

3) Inherent protection against over currents.

The vector control method is widely used in VSC-HVDC and it is suggested and adopted in this paper.

The vector control scheme involves representation of three-phase quantities in the dq synchronous reference frame. The transformation of phase quantities to dq - coordinates involves two steps: a transformation from the three-phase stationary coordinate system to the two-phase αβ stationary coordinate system and a transformation from the αβ stationary coordinate to the dq rotating coordinate system. Power invariant Clark and Park transformation are used to convert between the references frames [10].

The αβ frame enables one to transform the problem of controlling a system of three half-bridge converters to an equivalent problem of controlling two equivalent subsystems. The dq frame possesses the same merits as the αβ frame, in addition to the following [10]:

1) If the control is exercised in the dq-frame, a sinusoidal command tracking problem is transformed to an equivalent DC command tracking problem. Therefore, zero steady-state error is readily achieved by including integral terms in the compensators since the control variables are DC quantities. Hence, PI compensators can be used for the control.
2) In abc-frame, models of specific types of electric machine exhibit time-varying, mutually coupled inductances. If the model is expressed in dq-frame, the time varying inductances are transformed to (equivalent) constant parameters.
3) Conventionally, components of large power systems are formulated and analyzed in dq-frame. Therefore, representation of VSC systems in the dq-frame enables analysis and design tasks based on methodologies that are commonly employed for power systems, in a unified framework.

The instantaneous total (real) power in the time domain is expressed as [10]:

$$S(t) = v_a(t)i_a(t) + v_b(t)i_b(t) + v_{c(t)}i_c(t) \qquad \dots\dots\dots(4)$$

But in terms of dq frame variables

$$P(t) = \frac{3}{2}\left[v_d(t)i_d(t) + v_q(t)i_q(t)\right] \qquad \dots\dots\dots(5)$$

And

$$Q(t) = \frac{3}{2}\left[-v_d(t)i_q(t) + v_q(t)i_d(t)\right] \qquad \dots\dots\dots(6)$$

Equations (5) and (6) suggest that if $v_q = 0$, the real and reactive power components are proportional to id and iq, respectively. This property is widely employed in the control of grid-connected three-phase VSC systems.

As can be seen, the transformation into rotating dq coordinate system leads to the possibility to control the two current components, i_d and i_q independently. Thus independent control of active and reactive power is possible.

Proposed system for the Iraqi Super Grid (400 kV).

The main goal of this work is to develop, analysis and implement the Voltage Source Converter based High Voltage Direct Current transmission line for the Iraqi National super grid (400kV) which shown in Figure (4).

Figure (5) shows a schematic representation of VSC-HVDC system with a suggested model of a transmission line with length of 500 km is suggested between Khor Alzuber bus (KAZG) (AC system 1) and Baghdad South 400 kV bus (BGS4) (AC system 2). Both buses has a Short Circuit Level of 2667 MVA and 8200 MVA respectively.

Table (2) illustrates the proposed specifications selected for AC systems, transformers, switching frequency and DC cables at both stations.

Simulations Results

The dynamic performance of the transmission system for the proposed HVDC for the Iraqi super grid given in Table (2) is verified by using two simulating techniques:

1. Steps on the regulator references.
2. Recovery from severe perturbations in the AC system.

Step Responses

In order to test the dynamic responses of the VSC-HVDC regulators, three test cases have been studied. The simulation includes:

1) Active power is reversed at station 1(rectifier station) from -0.5pu to +0.5pu at t = 1.5 sec. active power reversion is shown in Figure (6), its reference control current Id is given in Figure (7).
2) Active power step change reference is changed from +0.5 pu to 1pu at station 1 at t = 2.5 sec. as shown in Figure (6). Figure (8) and (9) show the active power and its control current respectively at station2 in response to the change in station 1.
3) Reactive power reference is step changed from 0 to -0.3pu at t = 2 sec. then a step change from -0.3 pu to +0.3 pu at t = 2.7 sec. reactive power reference step change is shown in Figure (10) along with its reference control current Iq-ref as shown in Figure (11).

AC Side Perturbations

Two test cases have been studied. The simulation includes the single line to ground fault and 3-phase to ground fault.

1. Figure (12) and Figure (13) show AC system voltages and AC system currents at station 2 respectively which demonstrate the effect of the single line to ground (SLG) fault at phase A between the AC system and the converter transformer during 0.1 sec. (5 cycles) at t = 1.5 s. Figure (14) and (15) show the DC line voltage and the DC line current respectively.
2. Figure (16) shows AC system voltages at station 2 and Figure (17) shows AC system currents at station 2 which demonstrate the effect of the three phase to ground fault at station 2 (inverter station) between the AC system and the converter transformer during 0.1 sec. (5 cycles) at t = 2 s. Figure (18) and Figure (19) show the DC line voltage and the DC line current respectively.

CONCLUSIONS

This paper presents the steady-state and dynamic performances of VSC based HVDC transmission system during step changes of the active and reactive powers for the Iraqi super grid. These analyses are carried out for balanced and 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 bi-directional 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. However, during a three-phase fault; the decreased voltage at the converter terminals strongly reduces the power flow by the DC link. When the fault is cleared, normal operation is recovered fast.

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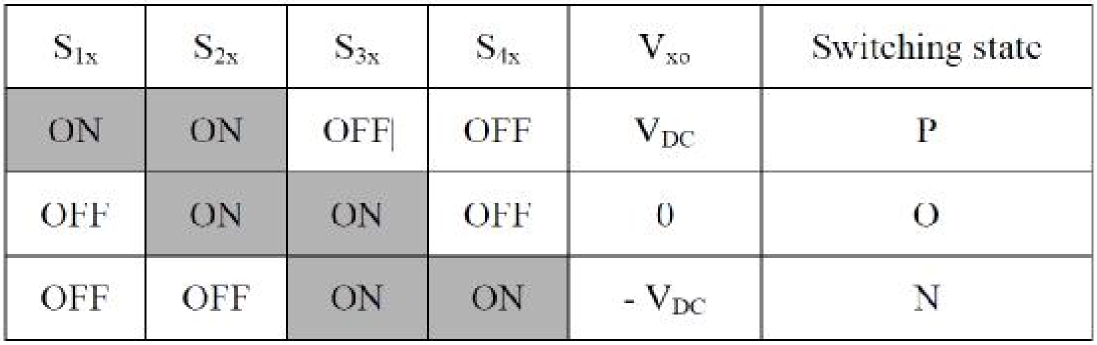
Table (1): The switching combination for the switches in each phase leg of the three level neutral-point-clamped voltage source inverter (x Î {a, b, c}).



S_{1x}	S_{2x}	S_{3x}	S_{4x}	V_{xo}	Switching state
ON	ON	OFF	OFF	V_{DC}	P
OFF	ON	ON	OFF	0	O
OFF	OFF	ON	ON	$-V_{DC}$	N

Table (2): the proposed specifications selected for AC systems, transformers and filters at both stations for the Iraqi super grid.

Station 1 (Rectifier side)	400kv (80°), 2667 MVA, SCR = 6.67, L1 = 140.91 mH, R = 31.46Ω, L2 =70.44mH.
Station 2 (Inverter side)	400kV(80°), 8200 MVA, SCR = 20.5, L1 = 45.83 mH ,R = 10.234 Ω, L2 =22.91mH
Transformer	Yg/Δ, 400kV/200kV, 400 MVA, 15%
Switching frequency	1350
DC Cables	500km×2 (R=0.0139 Ω /km, L = 0.159 mH/km, C = 23.1 μF/km)

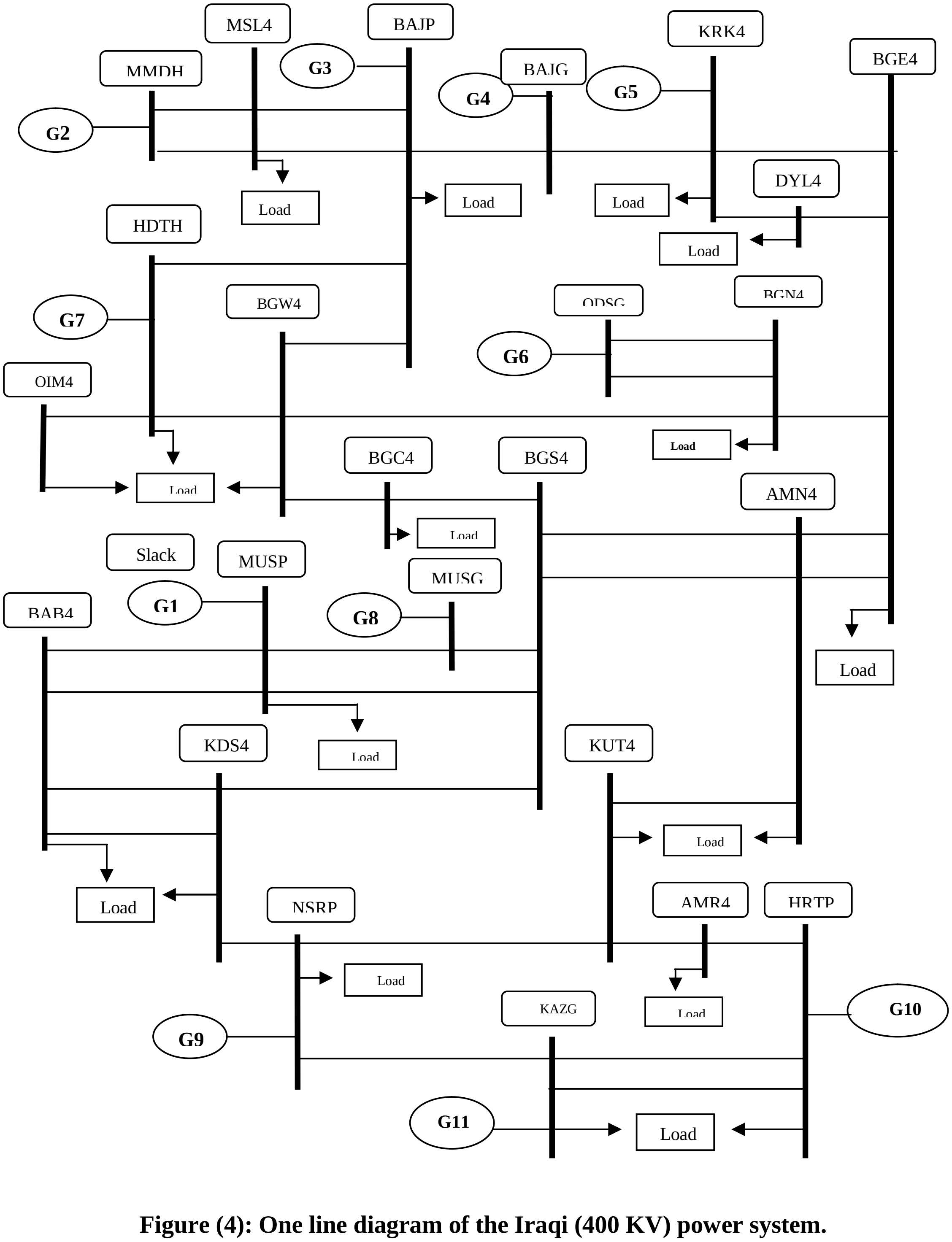


Figure (4): One line diagram of the Iraqi (400 KV) power system.

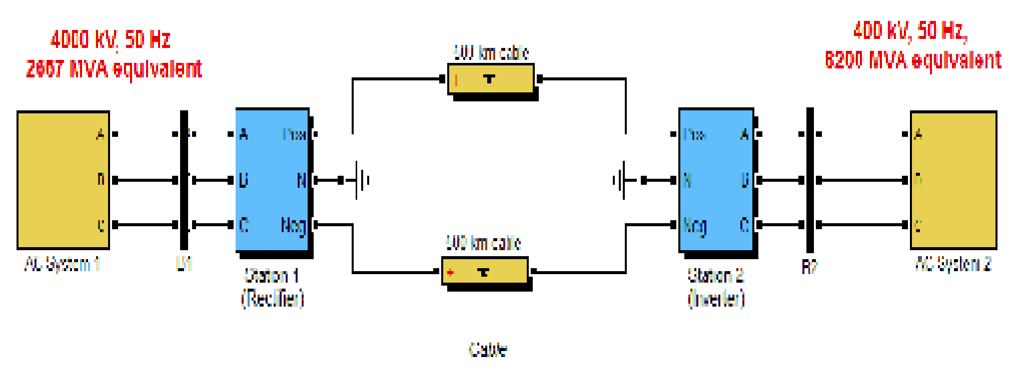


Figure (5): Schematic representation of the proposed VSC-HVDC system.

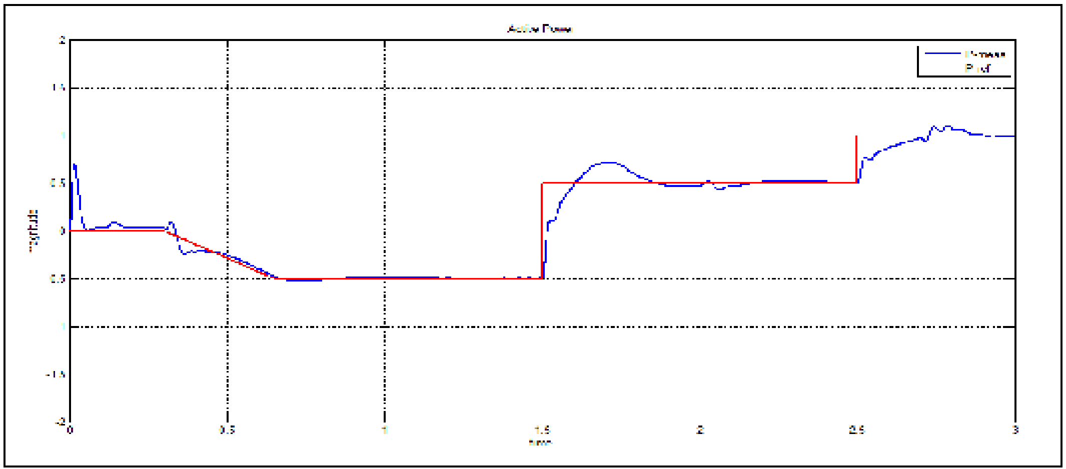


Figure (6): active power reversion and step change at station 1

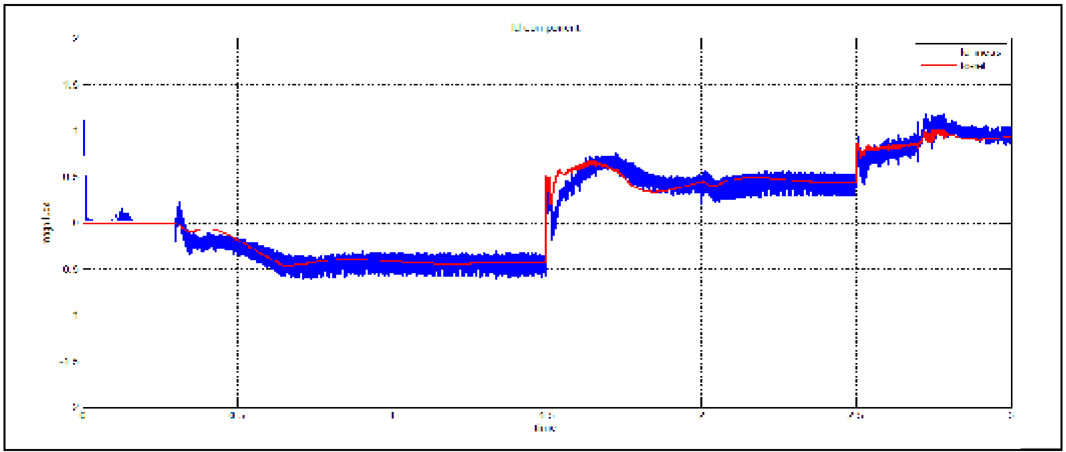


Figure (7): d-component of the reference control current (Id-ref) at station 1

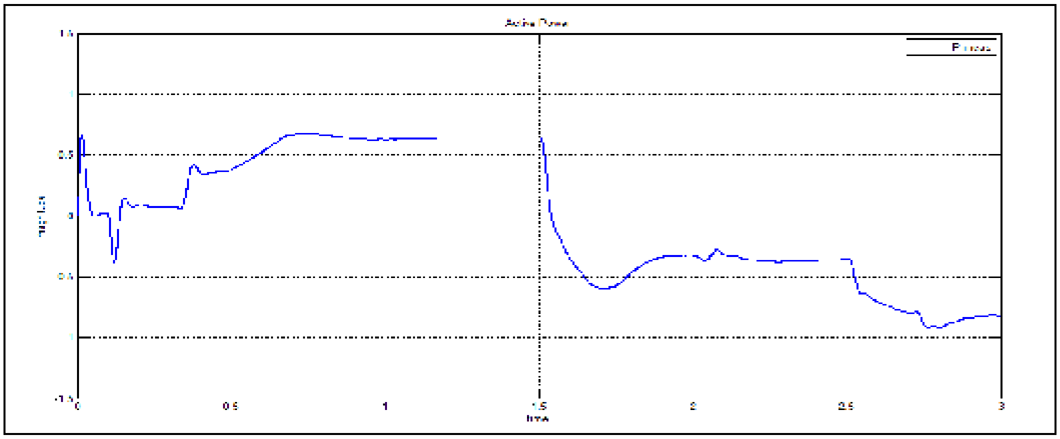


Figure (8): active power at station 2.

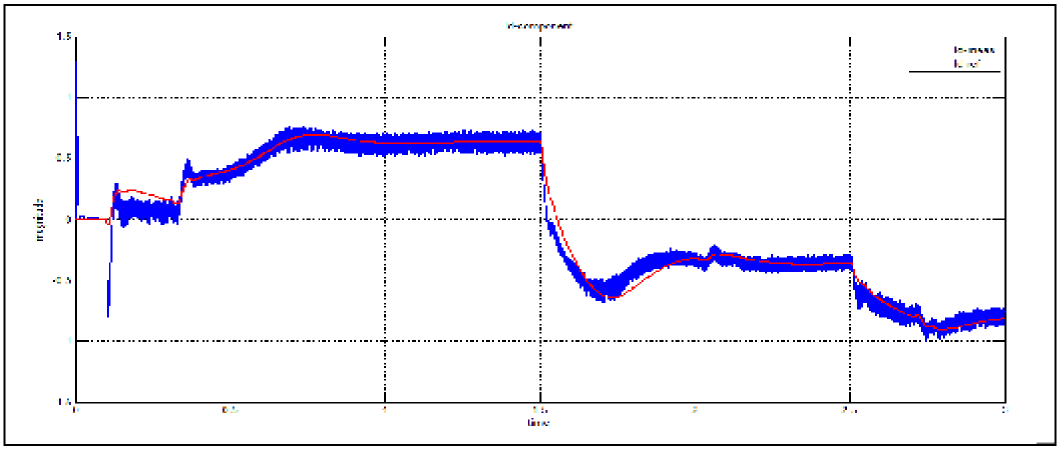


Figure (9): d-component of the reference control current ($I_{d\text{-}ref}$) at station 2.

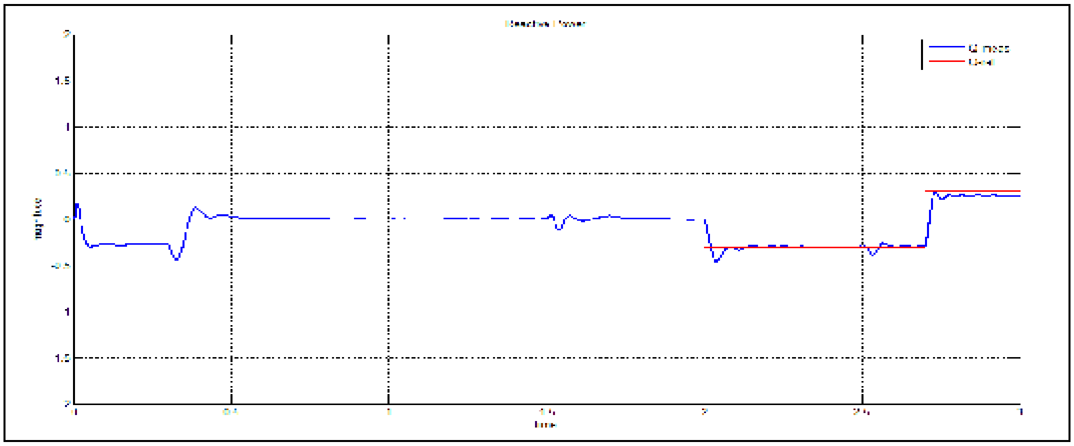


Figure (10): reactive power step change at station 1.

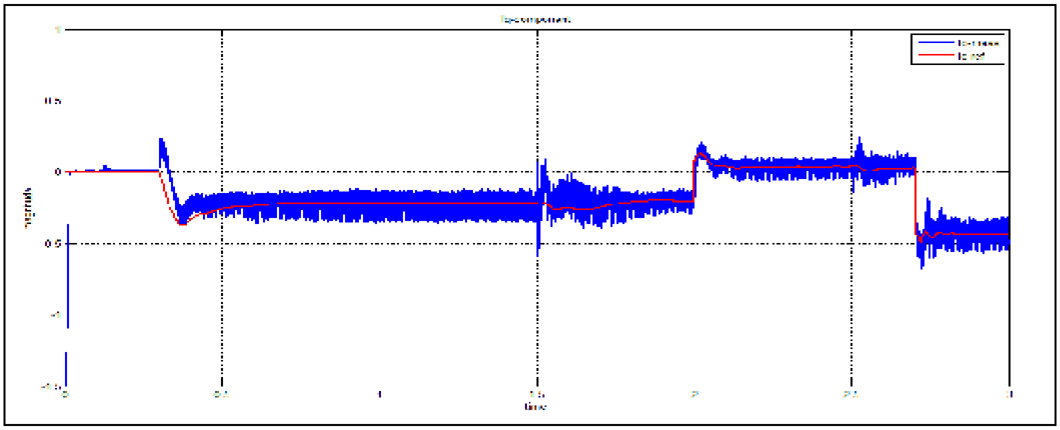


Figure (11): q-component of the reference control current ($I_{q\text{-ref}}$) at station 1.

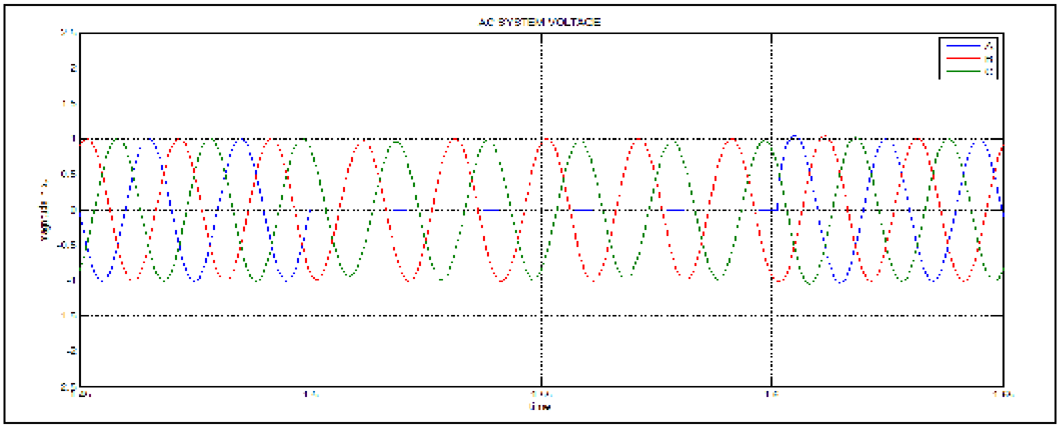


Figure (12): AC system voltages at station 2 with SLG fault at t = 1.5 sec.

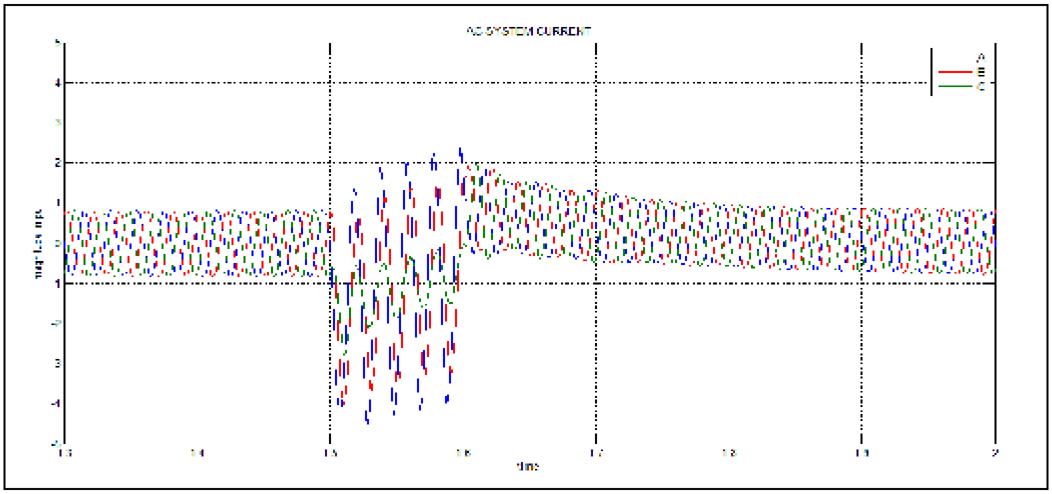


Figure (13): AC system current at station 2 with SLG fault at t = 1.5 sec.

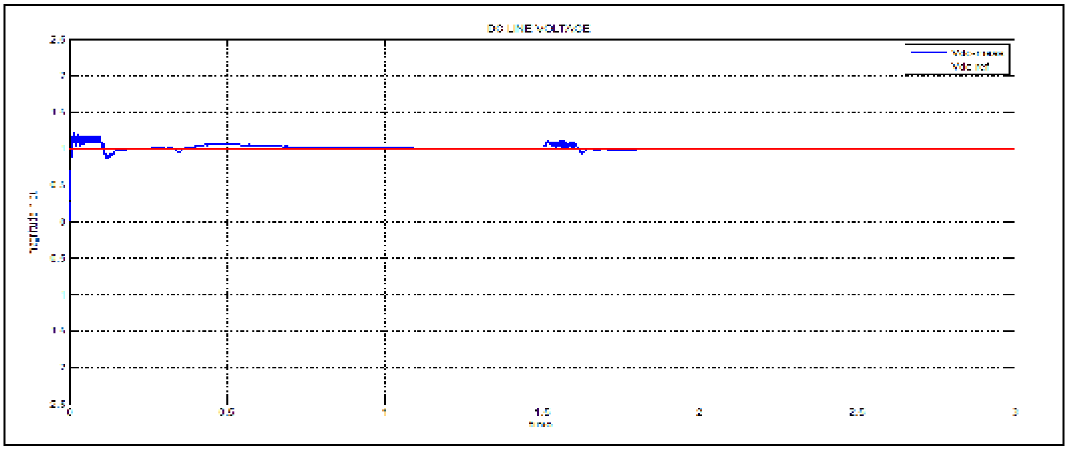


Figure (14): DC Line voltage with effect of SLG fault.

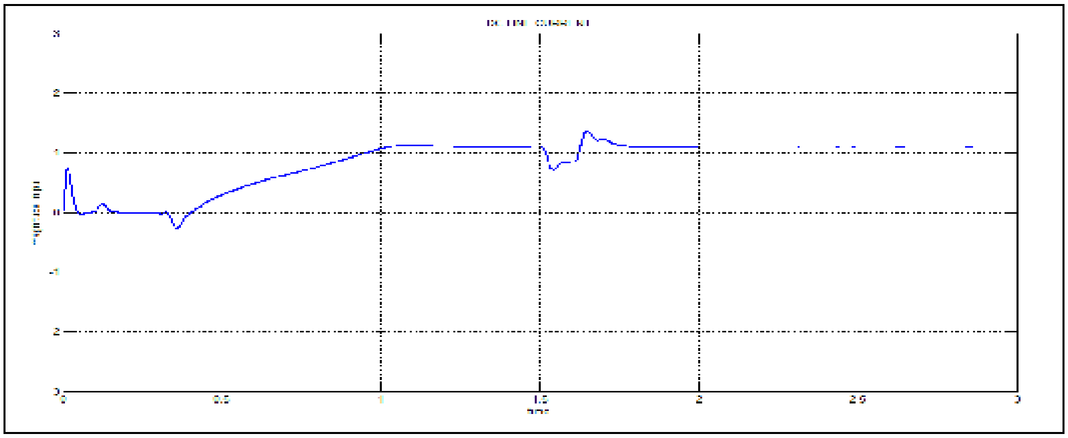


Figure (15): DC Line current with effect of SLG fault.

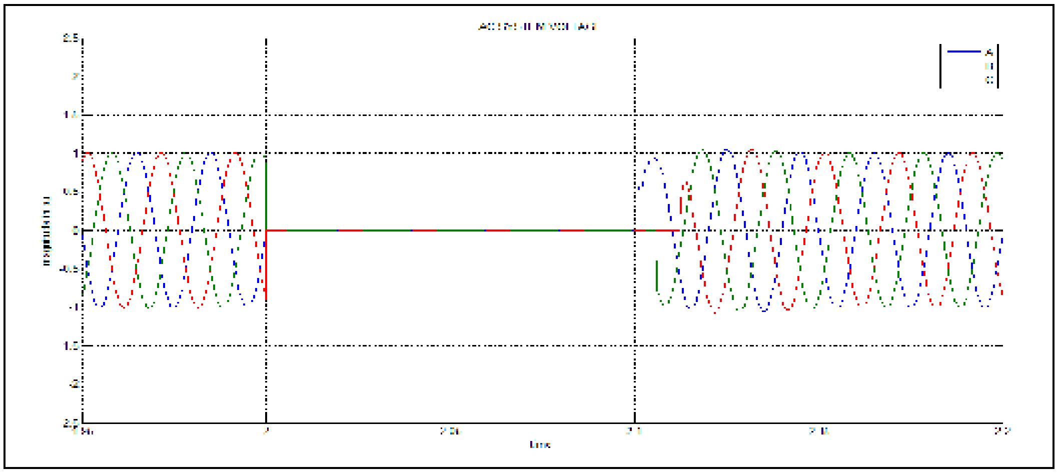


Figure (16): AC system voltages at station 2 with 3-ph fault at t = 2 sec

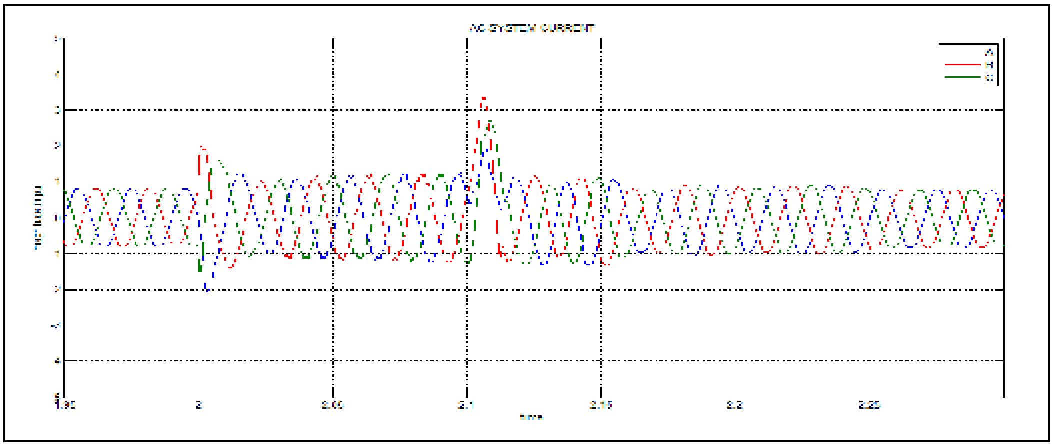


Figure (17): AC system currents at station 2 with 3-ph fault at t = 2 sec.

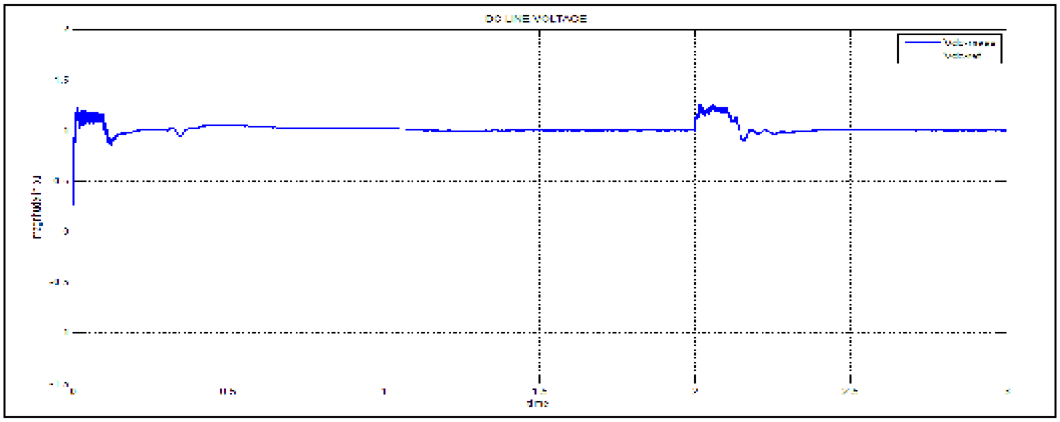


Figure (18): DC Line voltage with 3-ph fault at t = 2 sec.

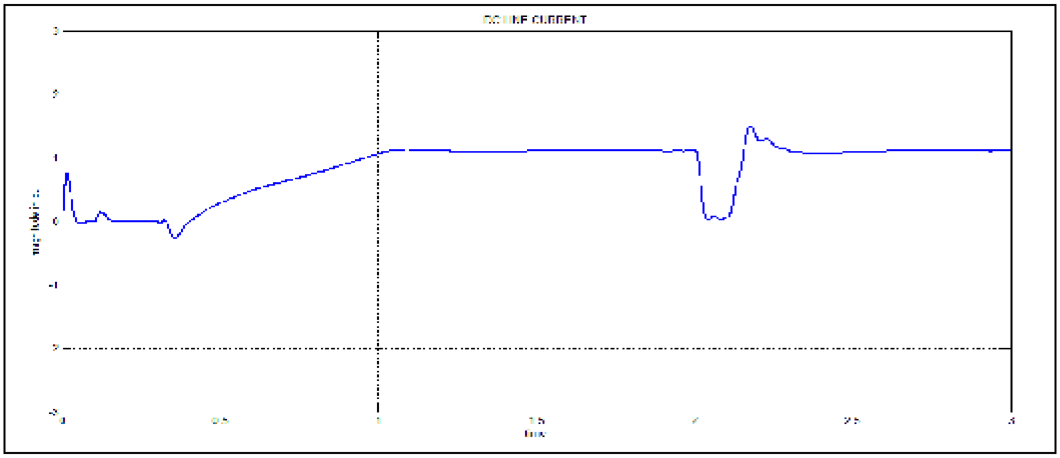


Figure (19): DC Line current with 3-ph fault at t = 2 sec.