Performance Evaluation of Constant Current HVDC Transmission Line

Giddani Kalcon, Abdelaziz Y. M. Abbas

Abstract—**This paper investigates the uses of line commutated converter HVDC in transmission of power between regional networks. The LCC-HVDC comprises of Line-commutated Converter at sending and receiving ends connected with DC link. The sending end converter operates with constant current mode while the receiving end operates with constant extinction angle. The investigation includes control of transmission and the ability of the system to recover when three phase faults occurs. Time-domain simulations conducted in Matlab/Simulink are used to validate the performance of LCC-HVDC**

Index Terms— **Constant current control, HVDC, Frequency stability, and voltage source converter.**

I. Introduction

Due to the rapid increase in electricity demand, the need arises for the interconnection of power networks distributed in different areas to increase supply reliability, and to facilitate power exchange between areas. The interconnection of separated networks results in a large power system expanding hundreds and even thousands of kilometers. In this large power system, high-voltage alternating current lines (HVAC) are used to accommodate the power over long distances between the different networks. HVAC lines have proven to be effective in transmission and distribution of electrical power but this creates challenges for power system operators such as [1-3]:

1- The transmission losses are so high in HVAC system
2- The ac transmission system requires expensive reactive power compensation at both ends of the line to avoid voltage problems
3- Non-synchronized grids operation is not possible.
4- In synchronous connections as in ac systems, the operation of the tie-line may cause power oscillations; moreover the fault in part of the network will propagate and affect the whole system.

High-voltage direct current (HVDC) transmission has been extensively researched over the last six decades as an alternative to conventional HVAC transmission systems. HVDC systems address most of the challenges associated with HVAC facilitating power transmission over long distances, prevention of disturbance propagation, connection of non-synchronized grids, and long submarine cable transmission.

The first generation of HVDC converters is based on line-commutated converters with naturally-commutated thyristors (LCC-HVDC). HVDC systems based on voltage source converter (VSC-HVDC) are the latest development in dc transmission, manufactured by ABB with the name of HVDC-light and by Siemens under the name of HVDC-plus. This technology uses IGBT devices which can switch ON/OFF the current.

LCC-HVDC system is well proven technology and has been used for power transmission in any countries. They has many advantages over conventional HVAC system when it comes to power transmission over long distances such as [4-5]:

- Low transmission losses for the same power capacity.
- HVDC transmission can carry up to 2.5 times the capacity of an ac line of similar voltage.
- Asynchronous connection of two ac systems.
- Reduces the dependency on the short circuit ratio (SCR), which is critical in the connection of ac systems with low short circuit ratios.
- Power flow is fully controlled (magnitude and direction).

However LCC-HVDC need large amount of reactive power in normal operation because the converter is operate at lagging power factor. Also, connection of filter is necessary to eliminate the generated harmonics.

LCC-HVD designed to transmit the power in one direction (for unidirectional operation) because the power reversal of the power requires the dc link polarity reversal [6].

There are several studies in the open literature to studies the performance of LCC-HVDC in normal and transient conditions. The authors in [7] developed multi-infeed HVDC system and present detailed analysis of the interactions between HVDC controllers and other dynamic devices. In order to cover the range of frequencies of interest the HVDC links are modelled in detail, including the rectifier current controller and the inverter extinction angle controller, which are commonly used in research studies. The analysis is carried-out using small signal stability technique.

LCC-HVDC system is considered in this paper because it has a potential to become the workhorse for large-scale power transmission over long distance with minimum cost and high technical benefits. In large countries with remote generation and far loads centre such as Sudan, the LCC-HVDC is the suitable solution for power transmission.

II. Stem lay-out

The steady-state and transient behavior of the LCC-HVDC transmission system is investigated using a complete 12-pulse converter model. The investigation includes: system behavior during ac faults and sudden changes in active power. The power is transmit from network1 to network2. The key results are illustrated together with supplementary details. The

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studied system is shown in Fig. 1 and the system parameters are listed in Table blow. The control strategies are implemented to control the current at the rectifier and to control either the voltage or the extinction angle at the inverter.

Rectifier side	Transformer:500/200/200kV, 1000MVA, 60Hz, transformer reactance are: 0.24, 0.12, 0.12 pu, transformer resistance are: 0.0025, 0.00125, 0.00125 pu, 600MVA ac filter
dc side	V_{dc}=500kV, P_{dc}= 1000MW, DC reactor L_{dc}=0.75H, dc cable resistance R_{dc}= 0.015Ω/km, dc cable length= 250km,
Inverter side	Transformer:500/200/200 kV, 1000MVA, 60Hz, transformer reactance are: 0.24, 0.12, 0.12 pu, transformer resistance are: 0.0025, 0.00125, 0.00125 pu, 600MVA ac filter

III. SYSTEM MODEL

Regarding HVDC shown in Fig.2, the mean dc voltage for rectifier operation is [8-9]:

$$U_{dcr} = \frac{3\sqrt{2}}{\pi} U_{Lr} \cos\alpha - \frac{3I_{dc}\omega L_c}{\pi} = \frac{3\sqrt{2}}{\pi} V_{Lr} \left(\cos\alpha + \cos(\alpha+\mu)\right) \quad (1)$$

And the dc current is given as:

$$I_{dc} = \frac{v_{ab}}{\sqrt{2}\omega L_c}\left(cos\alpha - cos(\alpha+\mu)\right) \quad (2)$$

For the inverter operation the mean dc voltage is expressed by the following equation [15]-[19]:

$$U_{dci} = \frac{3\sqrt{2}}{\pi} V_{Li} \cos\gamma - \frac{3I_{dc}\omega L_c}{\pi} = \frac{3\sqrt{2}}{\pi} V_{Li} \cos\beta + \frac{3I_{dc}\omega L_c}{\pi} = \frac{3}{\sqrt{2}\pi} V_{Li}\left(\cos\beta + \cos\gamma\right) \quad (3)$$

Where β is angle of advance and γ is extinction angle.
The power balance between its ac and dc sides can be expressed as:

$$\sqrt{3} V_{Lr} I_{acr} \cos\theta = \frac{3\sqrt{2}}{\pi} V_{Lr}\left(\cos\alpha + \cos(\alpha+\mu)\right) * I_{dc} \quad (4)$$

where θ is the phase angle at which the current lags the ac voltage and I_{ac} is the fundamental amplitude of the ac current. The expression for the power factor for rectifier and rectifier are

$$\cos\theta_r = \frac{1}{2}\left(\cos\alpha + \cos(\alpha+\mu)\right)$$
$$\cos\theta_i = \frac{1}{2}\left(\cos\gamma + \cos(\beta)\right) \quad (5)$$

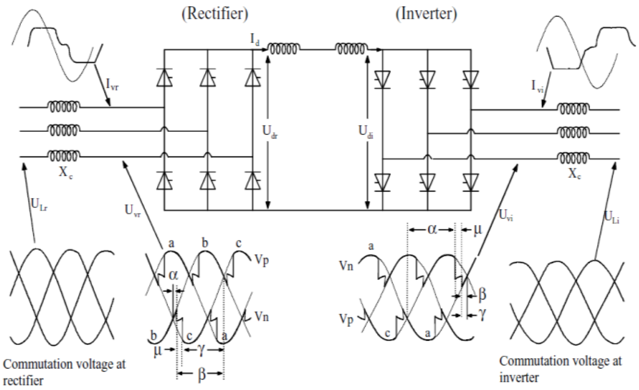


Fig.2 HVDC System

Fourier analysis of voltage waveform of 12 pulse converter contains harmonics of order 12*k*±1 with k odd (11^{th}, 13^{th}, 23^{th}, 25^{th} …). For this reason a passive filter is connected in converter station to eliminate 11^{th} and 13^{th} harmonics orders [9]. The harmonic spectrum of voltage waveform of 12 pulse converter is shown in Fig.3

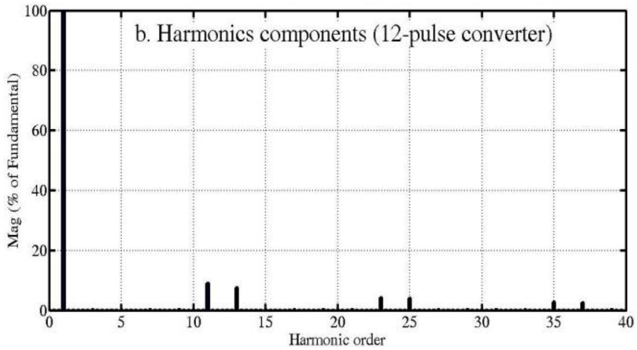


Fig.3 harmonic spectrum of 12- pulse converter

IV. HVDC CONTROL SYSTEM

The main functions of the control system in an LCC-HVDC transmission system are to control the power flow between the sending and receiving end converters, and to protect the equipment against over-current and voltage stress. The basic desired features of an LCC-HVDC control system are [10-11]:

1. Limit maximum dc current using constant-current control in the rectifier to protect the converter valves.
2. Maintain maximum dc voltage using constant voltage control in the inverter to reduce the losses in transmission line
3. Operation with lowest possible consumption of reactive power, that is, with the smallest possible delay angle (α) and extinction angle (γ).
4. Prevent commutation failures at the inverter hence improving the stability of the power transmission.

The control of power flow in an LCC-HVDC system is achieved by synchronizing the firing pulses generated by the trigger unit. The rectifier during normal operation is operating at constant current control (CC) by changing the delay angle until α is less than the minimum limit, then the rectifier will operate at constant-ignition angle (CIA). The sending end converter is regulates the power flow between two converters.

Fig.4 shows the block diagram of the rectifier constant current control system. The actual dc current flowing in the dc link is compared with the reference value I_{ord}. The resultant error signal I_e is then passed through a PI controller, the output of the PI controller is the alpha order α_{ord} which controls the frequency output of the VCO. A limit is used to prevent the dc current from exceeding the specific value to provide over-current protection to converter valves.

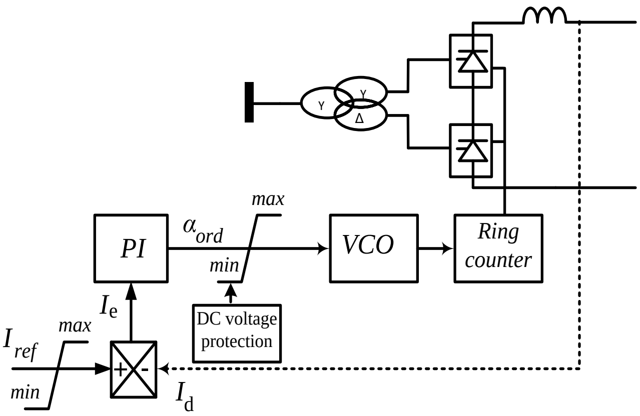


Fig. 4: Rectifier control system layout.

The control system at receiving end is selective. A control angle selector is placed to choose the desired control l from the dc voltage controller, extinction angle control, or current regulator. The selector chose the control with minimum firing angle. The control system is similar to the rectifier control system including the comparing loop, PI controller, VCO, and counter ring. The schematic block diagram of the inverter control system is shown in Fig. 5.

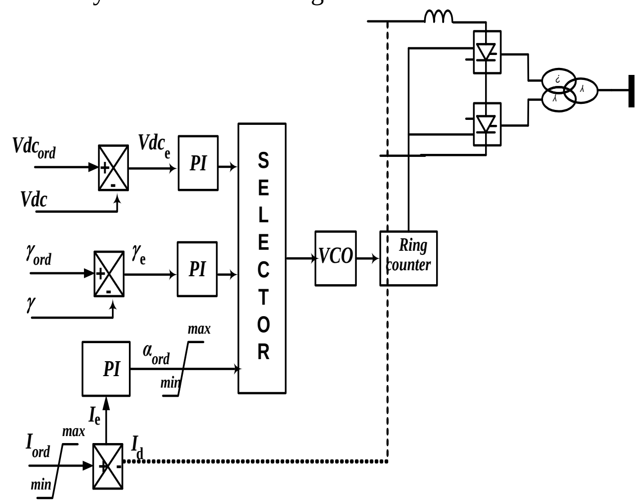


Fig. 5: inverter control system layout

V. SIMULATION RESULTS

HVDC to transmit the power between two regional networks with constant current control the following scenarios are investigated:

1- The first scenario considers change in transmitted power.
2- The second scenario considers symmetrical fault at inverter side.

A. System behavior during change in transmitted power

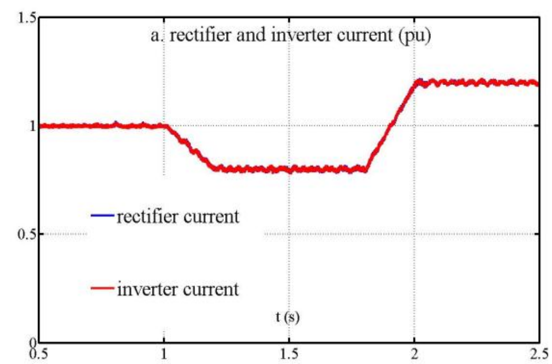
The dc link power can be increased or decreased using power run-up and run-down controls in response to local or remote disturbances. The step power change is achieved by adjusting the current reference value. The dc system behaviour during a sudden power change is shown in Fig. 6. The difference between rectifier side dc voltage and inverter dc voltage is due to dc cable ohmic drop. The current reference value is stepped down at t=1s from 1.0pu to 0.80pu gradually with a slope during 0.2s, and then at t=1.8s, it steps up to 1.2pu during 0.2s as shown in Fig.6a.

The dc voltage at the inverter is kept at constant value by inverter controller resulting in constant dc voltage at the rectifier side as shown in Fig. 6d. The rectifier delay angle (α_r) is increased during power step-down and decreased during power step-up as shown in Fig 6c. Since the dc voltage is kept constant and $P_{dc} = V_{dc} * I_{dc}$, then the dc current is adjusted by varying the rectifier delay angle in order to change the transmitted dc power. The ac voltage at the inverter side is varied proportionally to the change in the transmitted power and this can be explained using the power balance equation:

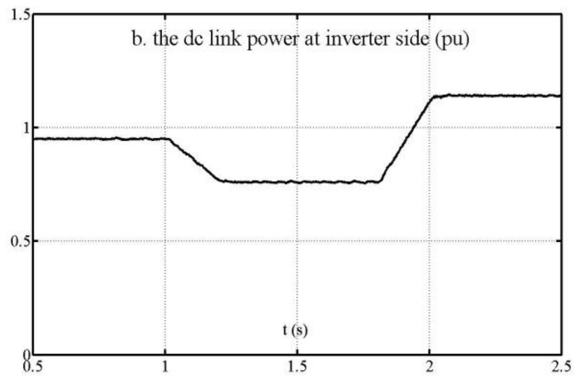
$$P = \sqrt{3} V_{l-l} I_{ac} \cos\theta = \frac{3\sqrt{2}}{\pi} V_{l-l} \left(\cos\alpha + \cos(\alpha+\mu)\right).I_{dc}$$

The Total Harmonic Distortion level (THD) on the ac sides is measured at B_1 and B_2. The results are compared with the harmonic level limit of 1.5% stated in the IEEE Std 519-1992. The THD in the ac voltage at bus B_1 is 0.593%, Fig. 6e shows the voltage waveforms at B_1 and B_2.

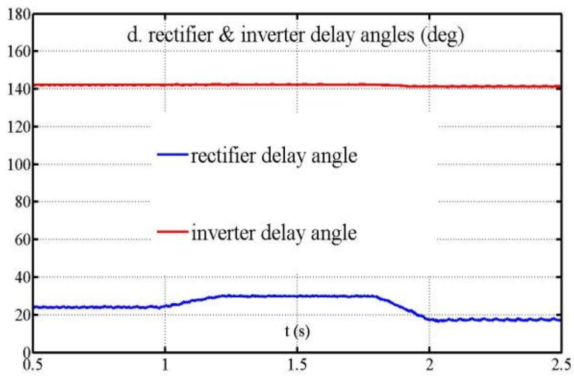
The ability of an LCC-HVDC transmission system to control the active power flow can be utilized to provide frequency regulation in the ac network. In this case the power control is activated when significant change in system frequency occurs. Therefore the transmitted power is varied to match the new power demand; the fast change of power achieved by dc control can improve the ac system transient stability and damping of electromechanical oscillations from nearby generators. One practical example of fast power command changes is the Pacific Intertie system where power command changes could be initiated at either the inverter or rectifier end and completed within 50 ms [12].



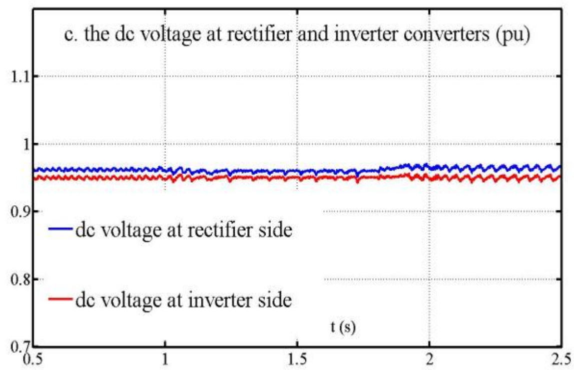
a- Rctifier and inverter currents



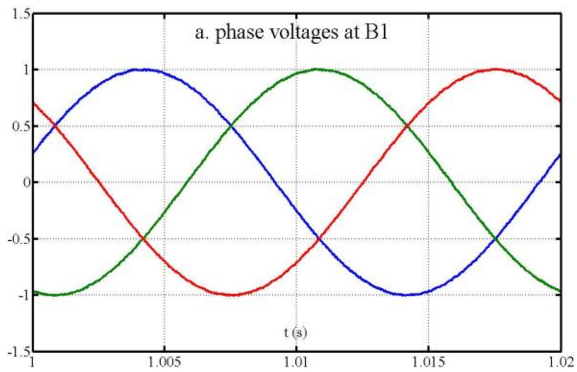
b- DC link power at inverter side



c- Rectifier and inverter delay angles



d- DC voltage at rectifier and inverter converter



e- Voltage at converter ac side

Fig. 6 Waveforms demonstrating HVDC performance during change in transmitted power

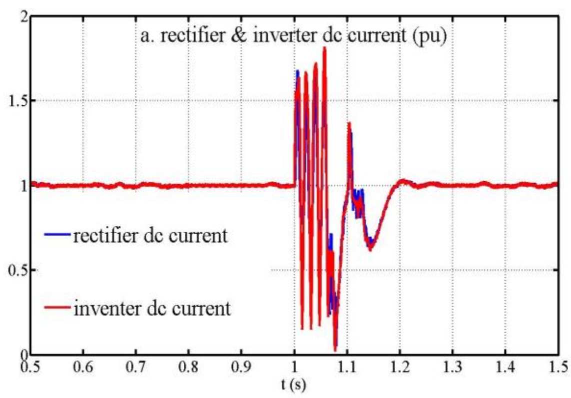
B. Scenario II: System behaviour during symmetrical fault at inverter side

An ac fault at the rectifier side will lead to temporary lose of the dc power in-feed to the receiving ac system. Depending on the ac system strength, an overvoltage may occur in the converters due to the reactive power compensation devices connected at the point of common coupling. If the fault occurs at the inverter side, commutation failure may be associated with the loss of the dc transmitted power.

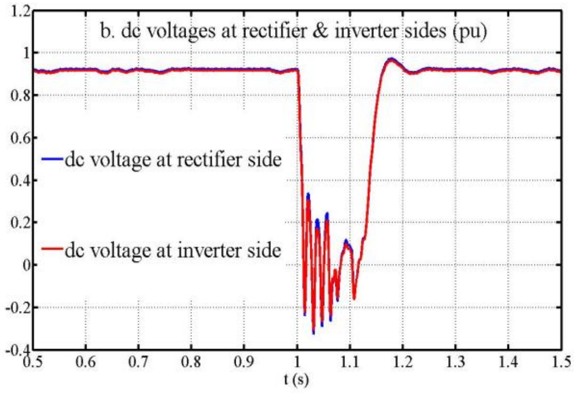
At time t=2s a solid three-phase fault-to-ground is applied close to B_2 at the ac side with a fault duration of 5 cycles (100ms for 50Hz). The results obtained from this scenario are presented in Fig. 7. When the ac fault occurs at the inverter side the inverter depressed terminal voltage will either reduce further or terminate the transmitted dc power, since $P_{dc} = V_{dc}.I_{dc}$, then both the dc voltages and dc currents will be affected by the fault. The V_{dc} and I_{dc} are altered during the fault period and recover after fault clearance (Fig. 7a and b).

The protection system forces the delay angle at the rectifier to increase and convert the operation mode to inversion (see Fig. 7c) when detecting a negative dc voltage caused by voltage reversal at the inverter side. Therefore the storage energy will discharge and the fault will be extinguished. The dc system current contribution to the three-phase short-circuits current is limited due to the dc system current rating, and no additional current is injected to the fault location compared to an ac interconnection. The short-circuit current level will depend mainly on the short circuit ratio of the ac system. Fig. 6h shows the ac current measured at bus B_2. In a practical LCC-HVDC system the time for the dc system to recover to 90% of its pre-fault power following ac fault clearing is typically in the range of 25 ms to 500 ms [12].

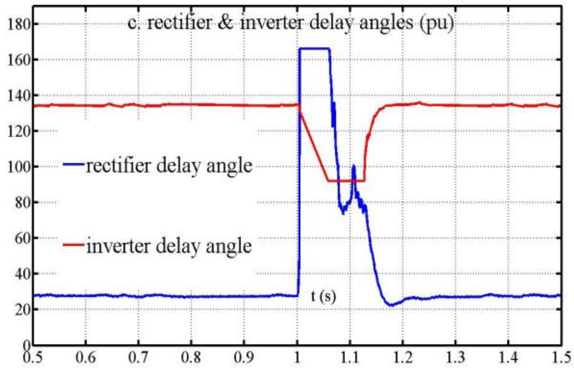
It was observed that in LCC-HVDC transmission system any disturbance in the receiving-end side will affect the sending-end side which results in non-decoupled operation of the two ac networks. This is explained by Fig. 7g, the voltage at B_1 is affected by the ac fault at B_2, this feature limits the use of LCC-HVDC systems for wind farm integration because the wind farm may be affected by the fault and open its breakers, and this may lead to black-out unless enough reserve generation is available.



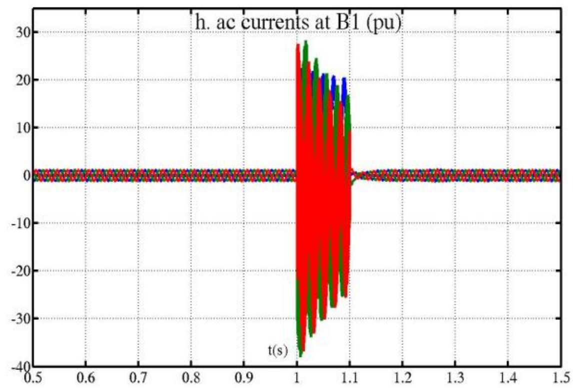
a. Rctifier and inverter currents



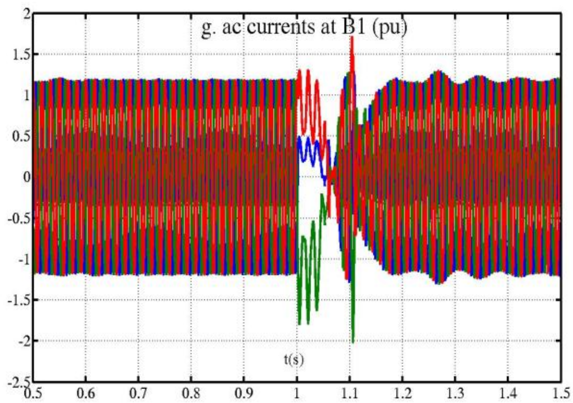
b- DC voltage at Rctifier and inverter sides



c- Rectifier and inverter delay angles



d- AC current at rectifier side (B1)



e- AC Current at rectifier side

Fig. 7 Waveforms demonstrating HVDC performance during symmetrical fault at inverter side

VI. Conclusion

This paper investigated the potential use of HVDC system for transmission of power between regional networks at steady state and transient conditions. It has been illustrated that this approach is so effective for large scale power transmission over long distance without reducing transmission losses. Also the HVDC system could be used to connect networks with different frequencies. The control system drive converter station is very important for stable operation. The PI parameters are chosen using small signal analysis. The robustness of the control is investigated during several conditions.

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