Analysis and Control of HVDC Transmission Power System

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Abstract—**This paper presents a design of converter controllers and filters of Line Commutated Converter High voltage direct current (LCC-HVDC) power transmission system to increase loadability and reliability of long power transmission. Also the proposed tuned PI controllers for HVDC Converters are verified in sense of HVDC transmission system performance and reliability. The studied system performances are compared with HVAC transmission systems in terms of power transfer quantity and reliability for a wide range of transmission distances and operating conditions. The Power Quality of HVDC transmission system is studied with Filters and proposed PI controllers .The two transmission systems (HVDC & HVAC) are simulated using MATLAB SIMULINK software package. With the control strategy, the HVDC system can provide a useful and economical way to transmit electric power over the long distance compared with HVAC system.**

***Index Term* -- LCC_HVDC, HVAC, modeling, steady state, power losses, harmonic analysis, MATLAB SIMULINK.**

I. INTRODUCTION

The industrial growth worldwide requires increased consumption of electrical energy; this has led to continual need of new concepts in the generation and transmission facilities to meet the increasing demand. Remote generation stations lead to the search for the efficient transmission system to transmit its power with reasonable costs and losses. Development of a Power converters with higher voltage and larger current lead that HVDC technology finds application in the transmission of remote generation power over long distances or by means of under-water cables, which are a critical component of a voltage source converter (VSC) HVDC transmission system in any offshore electrical power scheme [1], The transmission losses and the capital investments are eventually higher for AC systems beyond certain distance, e.g., typically about 700 Km for overhead and 40 Km for underground lines [2]. HVDC has more advantages than HVAC such as higher power capacity for one conductor where power transmitted using three phase HVAC lines can be transmitted using HVDC line with one or two conductors with small costs and losses, Simpler electrical line design, the ground return impedance is very small value for DC line which can operate as aground conductor , negligible charging current, HVDC Cables can be worked at a higher electric stress, Line power factor is always unity, line does not require reactive compensation, DC line can be used in parallel with AC line in interconnected power system to damp power oscillations , HVDC can connect between two AC system with different frequencies, Low short-circuit current on D.C line, power control and direction are very easy in HVDC systems[3]. Line Commutated Converters (LCC) and Voltage Source Converters (VSC) are the available two converters modes which can be used in HVDC systems. The VSC-HVDC has more advantages in its control system and is constantly increasing its power levels, however, LCC-HVDC still have more advantages, especially at powers from 400MW and above, line commutated converters need an external source of voltage and reactive power for their operation. Synchronous compensators or STATCOMs can be used to provide such services [4], [5]. Two terminal voltages of HVAC overhead lines and phase shafts (δ) between these voltages and the series inductive reactance of the line limit the steady-state stability and so on the power transfer capacity through this line, maximum power transfer occurs when phase angle equal to Ninety degrees .The reactance of the line which represented in line reactance, transformers, machines reactance's is directly proportional to the line length, power transfer capacity which limited by steady state stability is inversely proportional to the length of line .For stability requirement, the load angle is kept at relatively low value under a normal operating condition which cant exceeds Thirty degrees. In an uncompensated line the phase angle varies with the distance when the line operating at natural loads and puts a limit on the distance. The line distance can be increased using series compensator by adding a capacitor in series with the line which can provide a compensation for the line inductive reactance [6]. On the other hand, D.C transmission has no distance limitation because no stability problem as presented in AC transmission [3]. A lot of previous works try to analyze the reliability of HVDC over HVAC from different studied cases [7], [8], another previous simulation work has been carried out to represent modeling and control strategies of different schemes of HVDC system [9], [10], [11]. Steady state analysis and system recovering after any transient AC or DC faults conditions of the DC line connecting to a strong AC system presented in [12, [13]. In this paper, a simple model of a 12-pulse LCC- HVDC (High Voltage Direct Current) has been designed using Matlab/Simulink. A proper PI current controller using Ziegler-Nichols method and passive harmonic filters at rectifier and inverter stations are installed to improve transmission

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performance with long distances. The steady state operation of HVDC system is compared with HVAC system under the same generation, transmission length and load conditions.

II. STUDIED SYSTEM MODELING.

The studied system under steady state conditions consists of different components; the following sections describe the mathematical modeling of each component.

1. HVDC SYSTEM MODEL.

The Simulink model of amono-polar LCC-HVDC system is shown in Fig. 1 and described as follows:

A. AC System

The AC network at the rectifier side is represented as a power plant consisting of 6*350MVA synchronous generators transmitting a power to the load of 1630 MW (50 Hz, 500 kV, 0.8 lagging) at the inverter end through along HVDC transmission line [14].

B. Converter Station

A converter station consists of converter valve, converter transformer, smoothing reactor, AC filter, and DC filter. Converter station can be LCC which used thyristor valves or VSC which used IGBT valves. In case of LCC converter, converter units can be classified into 6-pulse and 12-pulse converter units. Usually most HVDC schemes employ the 12-pulse converter as the basic converter unit [9]. Two 6-pulse converter units are connected in series on the DC side and in parallel on the AC side to form a 12-pulse converter unit. Pulse bridges are connected in series with the intention of handle higher voltage levels. Two transformer units are used to feed the two 6-pulse converter units. These transformers are identical, but the purpose of obtained lower harmonics order in the AC side of the converter can be achieved by different connections in the two transformer windings, one of them is star- star connected while the other one is star-delta connected this lead to a phase shift of 30 degrees in the AC voltages. With this transformers windings arrangement, not only higher voltages can be obtained but also lower harmonic distortions. The phase shift cancels out certain harmonics leaving only those of order 12, 24, 36,…,12n at the DC side of the converter and those of order 11, 13, 24,…,12n±1 at the AC Side[17,12]. several filters are installed at both sides of the converters to eliminate the other remaining harmonics [15-17].

C. Harmonics filters and reactive power SOURCE AT AC side.

On AC side of 12-pulse HVDC converter, current harmonics are generated of the order of 11, 13, 24 and higher. In this paper two types of filters have been designed; single tuned passive filter, high pass filter, Filters are designed according to:

- Reactive power (Q) required for nominal voltage
- Tuning frequencies of orders 11, 13, and 24.
- Quality factor (q). It is determined by the resistance value which determines the sharpness of the tuning frequency.

So filter must operate as harmonic mitigation in high frequency and as reactive power source at fundamental frequency.

Reactive power required at converter is calculated as [20]

$$Q_r = Pd_r\, tan\left[arcos\left[\frac{cos(\alpha) + cos(\alpha + \psi_{r)}}{2}\right]\right] \quad (1)$$

$$Q_i = Pd_i\, tan\left[arcos\left[\frac{cos(\beta) + cos(\beta + \psi_{i)}}{2}\right]\right] \quad (2)$$

Where

The subscripts r and i denote the rectifier and inverter side respectively, and the angles α and β denote the firing angle of the rectifier and firing angle of inverter respectively, the overlap angles ψr, ψi can be calculated as in

$$\psi_r = arcos\left(cos\alpha - \frac{2 * X_C * Id}{\sqrt{2} * E_{tr}}\right) - \alpha \qquad (3)$$

$$\psi_i = arcos\left(cos\beta - \frac{2 * X_C * Id}{\sqrt{2} * E_{ti}}\right) - \beta \qquad (4)$$

Where

Id is the DC line current, Etr, Eti is the AC terminal voltage at rectifier and inverter respectively, Xc denotes the commutation reactance of the converter transformer.

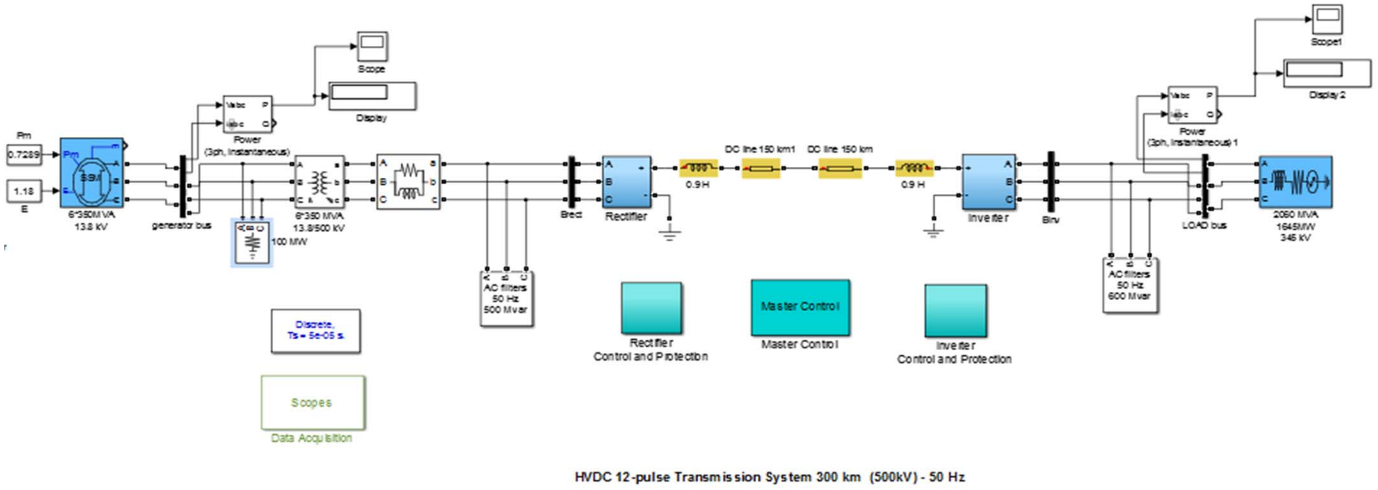

Figure 1. HVDC Matlab Simulink model.

TABLE I. HVDC LINK DATA

HVDC parameter &variables	rectifier	Inverter
Commutation reactance Xc(Ω)	5.5	6.5
Minimum control angle(deg)	10	15
Rated DC power at rectifier	1645MW	
Rated DC voltage at inverter		500KV
AC terminal voltage(Etr, Eti)	500KV	345KV

Using the data given in Table. I the overlap angles and reactive power consumption in rectifier and inverter are determined using equations (1, 2, 3, and 4).

C.1 Design of harmonic filters at rectifier side

At rectifier side:

$$Q_{cb} + Q_{f1} + Q_{f2} + Q_{f3} = Q_r \tag{5}$$

Where

Q_{cb}: The Capacitor banks reactive power at rectifier station.

Q_{f1}: The 11th harmonic filters reactive power value at fundamental frequency.

Q_{f2}: The 13th harmonic filters generated reactive power value at fundamental frequency.

Q_{f3}: The 24th harmonic filters generated reactive power at fundamental frequency.

a. Single tuned filter design

The single tuned filter is designed to eliminate the 11th harmonic and 13th harmonic as follows:

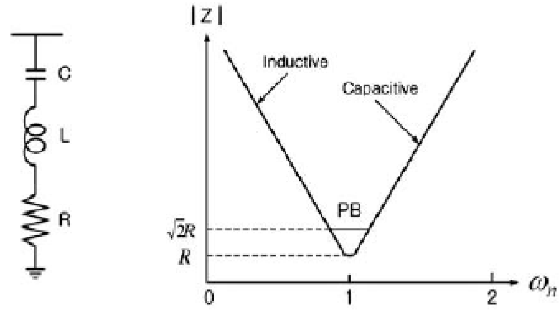

Figure 2. Single tuned filter and its impedance -frequency characteristics.

Let

C: filter capacitance.

L: filter inductance.

R: filter resistance.

Figure 2 shows single line diagram of single tuned passive filter and its characteristics [21].

Capacitance and inductance and resistance values of single tuned filter are calculated as:

$$C = \frac{Q_{f1}}{2\pi f V^2} \tag{6}$$

L value is determined from resonance condition (XL=XC) as given by:

$$L = \frac{1}{(2\pi f n)^2 * C} \tag{7}$$

$$R = \frac{\sqrt{L/C}}{q} \tag{8}$$

Where f is the fundamental frequency (f=50HZ), V is the line to line voltage; n is the harmonic order, q is the filter quality factor normally lies in the range between 40 and 100 for tuned filter branches.

b. High pass filter design

The high pass filter is designed to eliminate the 24th harmonic as follows:

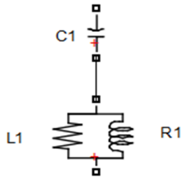

Figure 3. High pass filter.

The high-pass filter is a single-tuned filter where the inductance and resistance elements are connected in shunt instead of series, to provide a wide-band filter having impedance at high frequencies limited by the resistance value, Figure 3 shows single line diagram of high pass filter. High pass filters are designed at rectifier side to eliminate 24 harmonics. Filters tuned equation for inductance and capacitance calculation is similar to the single tuned filter equations (6, 7), but resistance is calculated as

$$R = q * \sqrt{L/C} \qquad (9)$$

Quality factor in case of high pass filter takes lower values between 2 and 10. Similarly for the inverter side three filters are designed to eliminate 11, 13, 24 harmonics. Table. II shows results of filter design at rectifier. Table. III shows result of filter design at inverter side.

TABLE II. FILTERS DESIGN RESULTS AT RECTIFIER SIDE

Harmonic order	11	13	24
Reactive power(Qf) MVAR	150	150	150
Rated voltage(V) kv line to line	500	500	500
Fundamental frequency(f) HZ	50	50	50
Quality factor(q)	100	100	3
Capacitance(c) µF	1.89	1.89	1.90
Inductance(L) mH	44.2	31.6	9.23
Resistance(R) Ω	1.52	1.28	208

TABLE III. FILTERS DESIGN RESULTS AT INVERTER SIDE

Harmonic order	11	13	24
Reactive power(Qf) MVAR	150	150	150
Rated voltage(V) KV line to line	345	345	345
Fundamental frequency(f) HZ	50	50	50
Quality factor(q)	100	100	3
Capacitance(c) µF	3.98	3.98	4.0
Inductance(L) mH	21.1	15	4.39
Resistance(R) Ω	0.727	0.614	99.2

The remaining value of reactive power required by HVDC converters at rectifier and inverter is supplied by using capacitor banks at both sides.

D. DC Side of the System Modeling

A smoothing reactor of 0.90 H for the rectifier and the inverter bridges connected in series with the DC line. The DC line is modeled in distributed parameter line model with lumped losses. Smoothing reactor works as DC harmonic mitigation and protect converter valve from a transient wave forms which caused by switching or over voltages stress through the transmitting system.

E. PID controllers tuning using Ziegler -Nichols method.

Tuning a PID controller using Ziegler Nicholas method as follows [18], [19]:

Using only proportional feedback control:

1. Reduce the integrator and derivative gains to 0.
2. Increase Kp from 0 to some critical value Kp=Kcr at which sustained oscillations occur as shown in Fig. 4.
3. from the waveform take the value Kcr and the corresponding period of sustained oscillation Pcr.

The controller gains are now calculated using Table. IV, for example according to Table. IV column no.2 and no.3 respectively Kp =0.45Kcr and Ki=0.54Kcr/Pcr for PI type controller design.

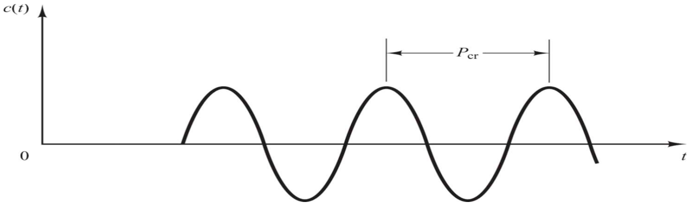

Figure 4. Ziegler Nichols Sustained oscillation.

TABLE IV. ZIEGLER-NICHOLS PID GAINS TUNING

Type	***Kp***	***Ki***	***Kd***
P	0.5Kcr		
PI	0.45Kcr	0.54Kcr/Pcr	
PID	0.6Kcr	1.2Kcr/Pcr	0.6KcrPcr/8

E.1 Proposed tuned PI controller at Rectifier station

A constant current at rectifier station is obtained by a PI current controller. The parameters of PI controllers are designed according to Ziegler Nicolas method. Current flowing through HVDC line is measured and then filtered using an appropriate filter and then it is compared to the reference current to produce an error signal which it is the input to tuned PI controller to produce firing angle order . of 12-pulse rectifier station as shown in Fig. 5.

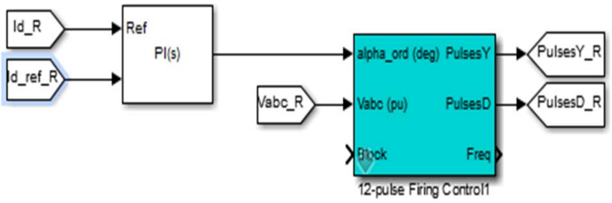

Figure 5. Proposed HVDC controller at rectifier station.

E.2 proposed tuned PI controller at inverter station

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HVDC line current and inverter side voltages is maintain a constant values during system operation by using a current controller and voltage controller at the inverter side, a gamma Controller for maintaining a constant extinction angle [17]. Current flowing through HVDC line is measured and then filtered using an appropriate filter and then it is compared to the reference current to produce an error signal which it is the input to tuned PI controller to produce firing angle order. For gamma controller the gamma value is measured using zero crossing information from the commutation bus voltages and the valve switching times. The gamma error is applied to another conventional PI controller, which produce the firing angle order for the inverter. The firing angle values of the three controllers are compared and for the minimum reactive power consumption by converters valves the minimum firing angle is used to produce the firing pulses for the inverter valves as shown in Fig. 6.

F. Voltage dependent current order limiters (VDCOL) function for HVDC reference current regulation.

In normal operation, the rectifier station controls the current at the reference value whereas the Inverter Controls the voltage at the reference value. The margin current and voltage values are respectively 0.1 p.u. and 0.05 p.u between both sides. VDCOL is implemented to change the reference current according the value of the DC voltage [8]. It is automatically reduces the reference current when the dc line voltage (Vd line) decreases to the set limit (as for example, during a DC line fault or a severe AC fault). Reducing the DC reference currents also reduces the reactive power demand on AC network, helping to cover the fault quickly. The VDCOL characteristics of the discrete 12-Pulse HVDC control are presented in Fig .7.

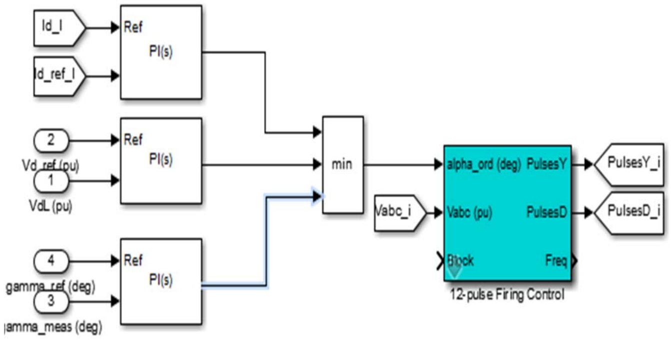

Figure 6. Proposed HVDC controller at inverter station.

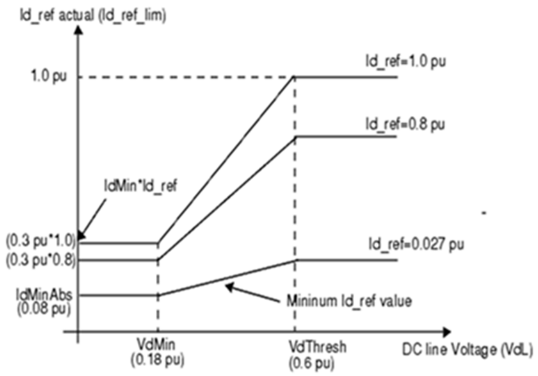

Figure 7. VDCOL characteristic; Id_ref = f (VdL)

2. HVAC SYSTEM MODEL

Power of 1680 MW (50 Hz, 500 kV, 0.8 lagging) is transmitted from a power plant Consisting of six 350 MVA generators to a sub-station through a three-phase HVAC transmission system with length of 300 km. at the receiving end of the HVAC line there is a substation of (345 kv,50 Hz, 1630MW) which receives this transmitted power.

III. SIMULATION RESULTS AND DISCUSSION.

1. HVDC SYSTEM

AC system1 at the rectifier end consists of a station of 6*350MVA synchronous generators with voltage level of 13.8KV which feeding AC system 2 consists of a substation of 2060MVA, with voltage level of 345KV through an HVDC link with proper control system as described previously.

A. Steady state simulation results.

Simulation is doing using MATLAB SIMULINK 2013. The rectifier station operates with firing angle about 14 degrees at steady state operation as shown in Fig. 8. Rectifier controller adjusts DC current value at 1pu (3.3KA) as shown in Fig. 9. Inverter operates at extinction angle about 142 degrees at steady state operation as shown in Fig.10. Inverter controller adjusts DC voltage of HVDC link at 500KV as shown in Fig. 11. Power is transferred through HVDC link from rectifier station to inverter station with very small losses as shown in power waveforms at generator bus in fig. 12, and at load bus as shown in Fig. 13. Load bus voltages and currents waveforms are shown in Fig. 14 and Fig. 15 Respectively. Harmonic spectrum and THD value are calculated at rectifier and inverter AC buses with and without proposed filters. Without filter and capacitor banks at both sides, rectifier and inverter voltage and current waveforms are distorted due to AC harmonics side of HVDC system as shown in harmonic analysis in Fig. 16 and Fig. 17. With using proposed Filters and capacitor banks THD will be reduced to the standard limit as shown in Fig. 18 and Fig. 19.

B. Effect of HVDC transmission length variation.

Different lengths (300,600,800,1000) km of HVDC link are introduced to study the effect of HVDC line length increasing in power transmitted through HVDC link . At each value of line length, the power at generator and load buses are plotted with time as shown in Fig. 20and Fig. 21 for 800Km length. Different losses in the system converters, transformers, shunt branches, transmitted line are measured with different line lengths as illustrated in Table. V.

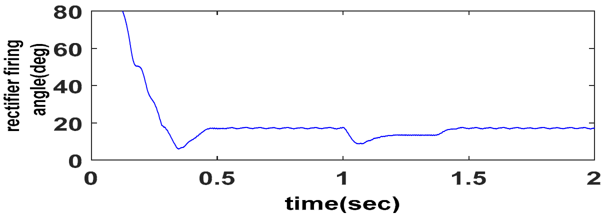

Figure 8. Rectifier firing angle of HVDC link

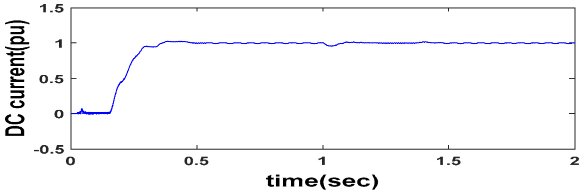

Figure 9. DC current of HVDC link

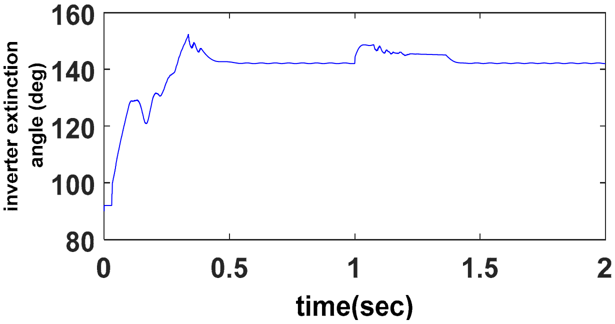

Figure 10. Inverter extinction angle of HVDC link

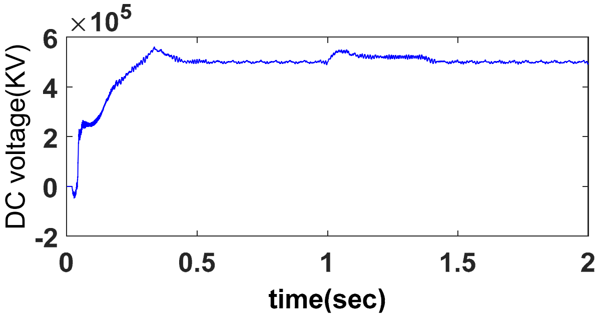

Figure 11. DC voltage of HVDC link

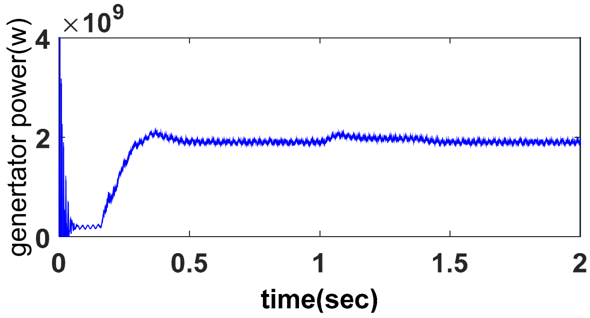

Figure 12. Active power Response at generator bus

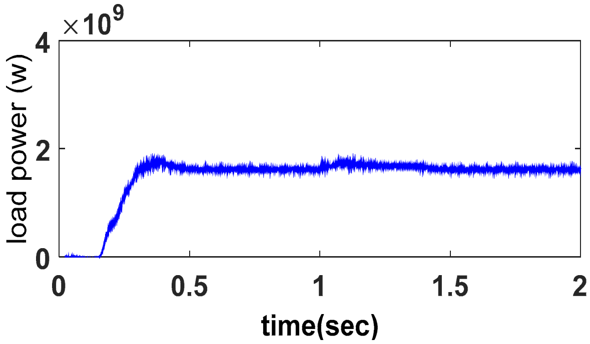

Figure 13. Active power Response at load bus

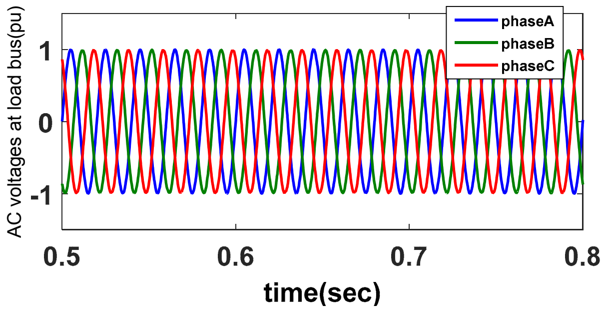

Figure 14. AC voltages at load bus

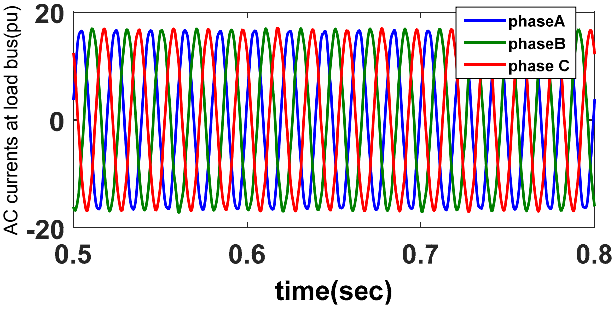

Figure 15. AC currents at load bus

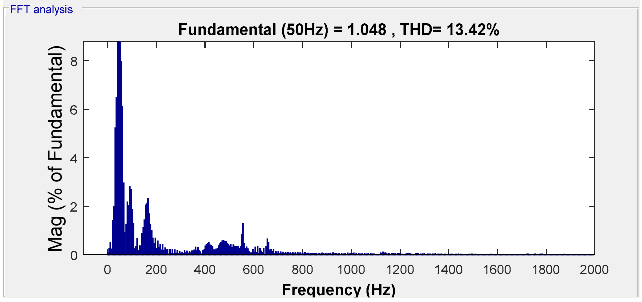

Figure 16. Harmonic analysis at rectifier bus without filters

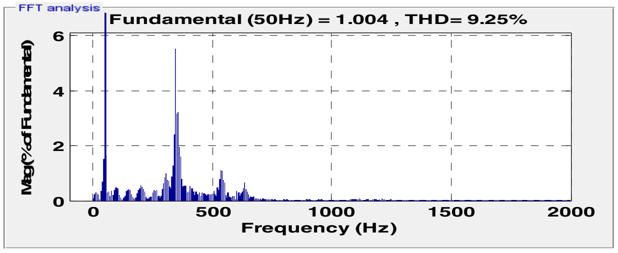

Figure 17. Harmonic analysis at inverter bus without filters

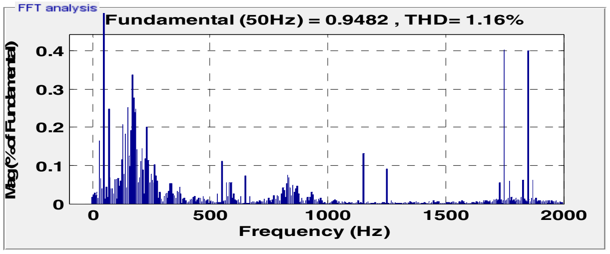

Figure 18. Harmonic analysis at rectifier bus with filters

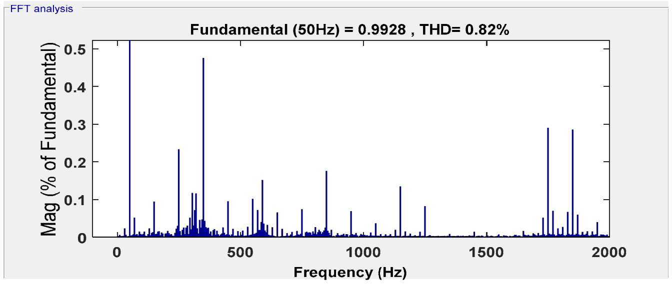

Figure 19. Harmonic analysis at inverter bus with filters

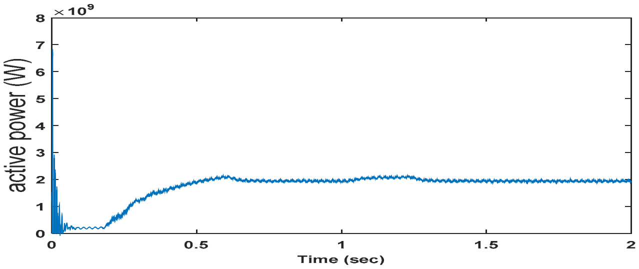

Figure 20. Active power Response at generator bus with 800Km length.

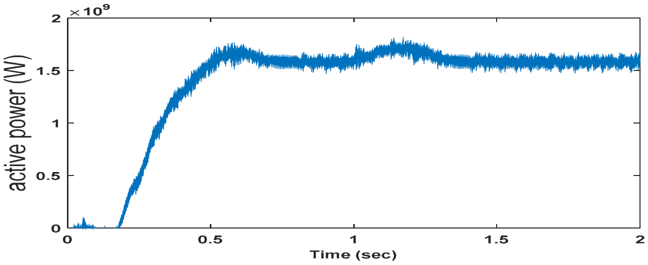

Figure 21. Active power Response at load bus with 800Km length.

TABLE V. Active power with different lengths of HVDC line

Length(Km)	300	600	800	1000
Load end power (MW)	1632	1617	1608	1585
Converters losses(MW)	10	20	50	55
DC line losses(MW)	97	109	121	128
Transformers &shunt branches losses(MW)	127	127	134	176
Generator power(MW)	1866	1873	1913	1944

2. HVAC SYSTEM.

A. Steady state simulation result.

With the Same generation and load conditions of HVDC system, power is transmitted from sending end to receiving end through three phase HVAC transmission line represented by three phase distributed parameters line. Simulation is doing using MATLAB SIMULINK. Active power response at generator and load ends are shown in Fig. 22 and Fig. 23 respectively. Voltages and currents wave forms at load end are plotted as shown in Fig. 24 and Fig. 25.

B. Effect of HVAC transmission length variation

Different lengths (300, 600, 800, and 1000) km of HVAC link is introduced to study the power transmitted versus the length variation of transmission line. It is noted that the power at receiving end will be reduced due to high losses, and stability problem of long transmission line as shown in in Fig. 26 and Fig. 27 with 800 km length, for system stability limit power angle not increase than 30 degree. The power capacity and system stability can be increased by using series compensator which adds more cost to the transmission system; this cost may be increased with the length increasing. Different losses in the system converters, transformers, shunt branches, transmitted line are measured with different line lengths as shown in Table. VI.

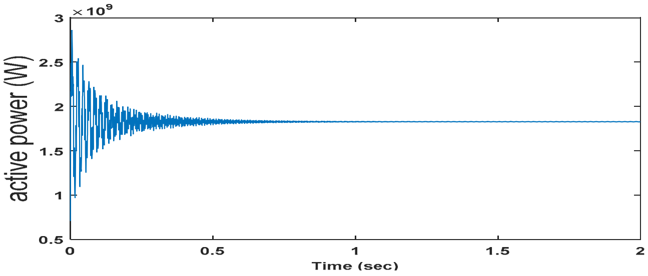

Figure 22. Active power Response at generator bus.

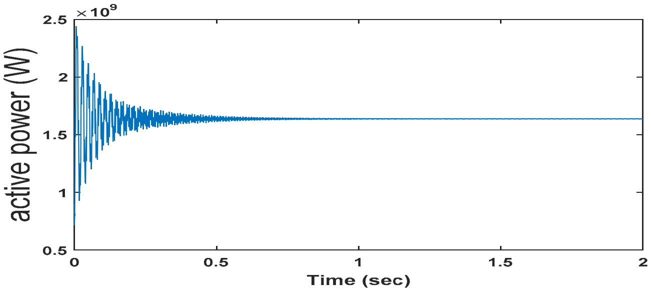

Figure 23. Active power Response at load bus

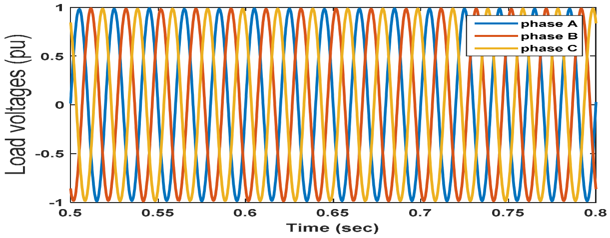

Figure 24. AC voltages at load bus

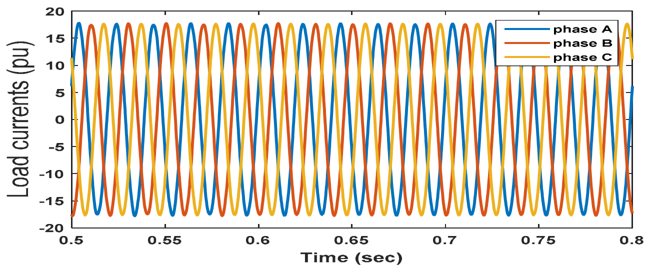

Figure 25. AC currents at load bus

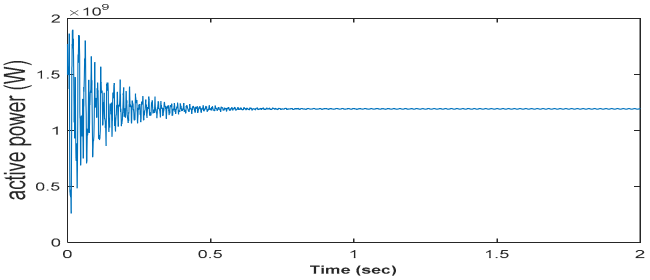

Figure 26. Active power Response at generator bus with 800Km length

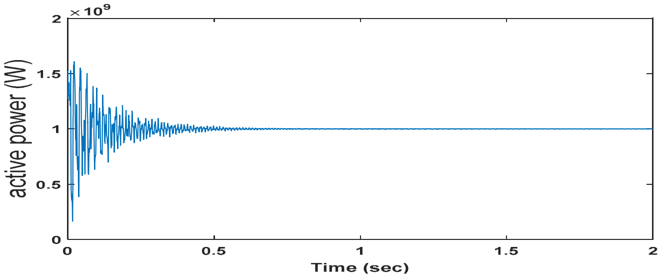

Figure 27. Active power Response at load bus with 800Km length

TABLE VI. ACTIVE POWER WITH DIFFERENT LENGTHS OF HVAC LINE

Length(Km)	300	600	800	1000
Load end power (MW)	1632	1145	999.7	925.1
Transformers &shunt branches losses(MW)	142	149	155.3	164
AC line losses(MW)	48	42	39	37
Generator power(MW)	1822	1336	1194	1126

IV. CONCLUSIONS

In this paper, a proposed modeling of Line-commutated converter HVDC system with a converter proposed PI controller's parameters design using Ziegler-Nichols method. About 25% overshoot and a good settling time can be obtained in the system response by using this designed converter parameters. Filters are designed as a reactive power source for HVDC converter station at the fundamental frequency and as harmonic mitigation at a higher frequency of AC harmonic orders generated in AC side of HVDC system to increase power capacity of transmission systems over a long distance. To ensure satisfactory operation and equipment safety, several limits such as minimum current limit, and VDCOL are provided to the control systems. A Comparative study between HVDC and HVAC systems according to the capacity of the power transfer with different lengths of the transmission line is introduced in this paper. Harmonic analysis with and without filters are also studied to show the quality of the proposed filters on HVDC system operation. Without transmission line, reactive power compensations, it is very difficult to transfer a bulk power at Long distances by using HVAC line with good efficiency because the power capacity of the HVAC line limited with the stability of the system and reactive power requirements of the transmission line which increase with the line length. An HVDC transmission have no distance limitation because of no frequency and hence no stability problem. Active power in the HVDC link is very easy to control.

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