HVDC Light Power Flow Modelling

Assignment No. 2
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***Abstract*—The power system analysis and design is generally done by using power flow analysis. The objective of this project is to develop a MATLAB program to calculate voltages and phase angle, active and reactive power at each bus using the Newton-Raphson method. At first 5 bus system is calculated with MATLAB Program and then IEEE 14 bus system MATLAB program is executed with the HVDC Light model with input data. This type of analysis is useful for solving the power flow problem in different power systems which will useful to calculate the unknown quantities and improve the voltage profile in nearby buses.**

***Index Terms*—HVDC, voltage source (VSC), voltage magnitudes (V), Active power (P), Reactive power (Q), Newton-Raphson (NR) method**

I. Introduction

Innovative solutions with HVDC and FACTS have the potential to manage new challenges. By means of Power Electronics, they provide features which are necessary to avoid technical problems in the power systems, they increase the transmission capacity and system stability very efficiently and help prevent cascading disturbances. HVDC Light is high voltage direct current transmission system based on solid state voltage source technology utilizes most advanced power electronics and semiconductors [1].

HVDC Light is the most recent HVDC technology based on Voltage Source Converters (VSC) and extruded DC cables with power units up to 200 MW. HVDC Light converters include Insulated Gate Bipolar Transistors (IGBTs) and operate with high frequency Pulse Width Modulation (PWM) in order to get high speed control of both active and reactive power. HVDC Light cable with insulation of extruded polymer and specifically adapted for direct voltage [2].

HVDC applications include cable transmissions, long distance HVDC transmissions with overhead lines and Back to Back (B2B) schemes to interconnect systems operating at different frequencies. HVDC VSC is the preferred technology for interconnecting islanded grids, such as offshore wind farms, to the power system. This technology provides the Black-Start feature by means of self-commutated voltage source converters [1].

Key HVDC Light issues include modular multi-terminal control, protection, reliability, and cable modelling and design. A VSC-HVDC cable has a complex structure consisting of multiple layers. The twin issues of converter interpretability and protection coordination remain key. It is to be expected that in future if large on- or offshore grids develop, then different manufacturers will be connecting their converters to the same DC network. Therefore, accurately predicting the availability of these links is of paramount importance. AC circuit breakers cannot be used in HVDC systems because it would involve time consuming de-energizing and re-energizing of DC system. Hence, passive DC circuit breakers, hybrid circuit breakers and all-solid state solutions are hot topics for research [3].

The 2-Level HVDC Light Generation 3 VSC technology is the worlds most powerful VSC project. It uses a significantly smaller site area than an equivalent-rated Line Commutated Converter HVDC project. This is at the expense of increased converter building size and higher losses. The use of a cascaded two-level VSC-HVDC converter offers a smaller overall site footprint and a lower building height than both the 2-level and LCC-HVDC alternatives. However, this is at the expense of increased converter building size. The losses for the latest generation of Cascaded Two Level VSC-HVDC technology are now comparable with those of the Line Commutated Converter HVDC technology [4].

One potential challenge faced by the cable system is new type of over-voltages occurring in the dc cable due to faults in the HVDC system depending on system topology and converter design. The cable generally needs to be designed to withstand the voltage occurring during a fault. When the impedance of the dc circuit suddenly reduces due to the fault, and at the same time the pole to ground voltage of the healthy pole is pushed up, all the inductances and capacitances of the system form an L-C oscillatory system and start to oscillate. While the surge arresters protect the cable close to the station terminals, the midpoint of the cable remains furthest away and is hence least protected. Rise and decay time of such over-voltage is longer than what is typically required in cable system qualification tests. Moreover, the magnitude of the over-voltage varies with the amount of transmitted power [5].

II. HVDC LIGHT

The HVDC Light comprises two voltage source converter (VSC), one operating as a rectifier other operating as inverter. The two converter are operating back to back OR joined together by DC cable. Its main function is to transmit constant dc power from rectifier to inverter station. The schematic representation of HVDC light shown in figure below [6].

It provides fast AC voltage control and superior voltage stability for Transmission up to 330MW, and for DC voltage in the 150kV range. HVDC Light provides independent control of active and reactive power, independent power transfer and power quality control, power reversal, reduced power losses in connected ac systems, increased transfer capacity in the existing system, fast restoration after blackouts, flexibility in design, no relevant magnetic fields, low environmental impact, indoor design and short time schedule [1].

It consists of Standard Power Transformers are used to regulate AC voltage for the operation of VSC. AC Filters provide low impedance paths for the harmonics in order to limit them from entering into the connected AC network.

VSCs are made using self-commutated IGBT valve stacks and operate with high frequency Pulse Width Modulation (PWM). They do not have any reactive power demand due to reactive power compensation using STATCOM and fixed filters. HVDC Light VSCs has no minimum short circuit capacity limit due to black-start feature. To switch voltages higher than the rated voltage, several positions are connected in series in each valve. Each IGBT position can be individually regulated in the valve to the correct voltage level. The flexibility of the IGBT makes it possible to block the current immediately if a short circuit is detected [1].

DC side capacitor provides a low inductance path for the turned off current, serves as an energy store and reduces the harmonic ripple on the direct voltage.

The DC transmission can be achieved using power lines, submarine DC cables or Long Distance Overhead Lines. Converter Reactors provide low-pass filtering of the Inverter output PWM pattern to give the desired fundamental frequency voltage, provide active and reactive power control and limit the short circuit currents [1].

One voltage source of the rectifier other voltage source of inverter linked together by a constrained power equation that is given below [6].

$$Vv_{R_1} = |Vv_{R_1}|(\cos\theta vR_1 + j\sin\theta vR_1)$$

$$Vv_{R_2} = |Vv_{R_2}|(\cos\theta vR_2 + j\sin\theta vR_2)$$

$$P_l = |V_l|^2 G_{vR1} - |V_l||V_{vR1}|G_{vR1}\cos(\theta_l - \theta_{vR1}) + B_{vR1}\sin(\theta_l - \theta_{vR1})$$

$$Q_l = -|V_l|^2 G_{vR1} - |V_l||V_{vR1}|G_{vR1}\cos(\theta_l - \theta_{vR1}) + B_{vR1}\sin(\theta_l - \theta_{vR1})$$

$$P_m = |V_m|^2 G_{vR1} - |V_m||V_{vR2}|G_{vR2}\cos(\theta_m - \theta_{vR2}) + B_{vR1}\sin(\theta_m - \theta_{vR2})$$

$$Q_m = -|V_m|^2 G_{vR1} - |V_m||V_{vR2}|G_{vR2}\cos(\theta_m - \theta_{vR2}) + B_{vR1}\sin(\theta_m - \theta_{vR2})$$

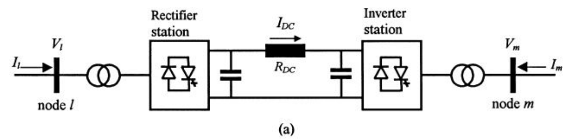

Fig. 1: HVDC Light model

The equivalent representation of HVDC Light model is given below. One VSC converter control DC voltage the other control active power through the DC link.

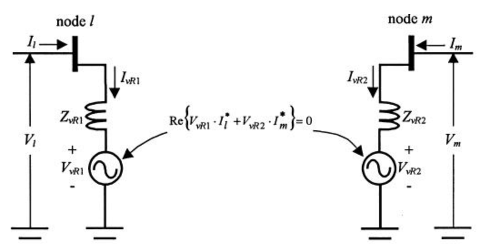

Fig. 2: Equivalent HVDC Light model

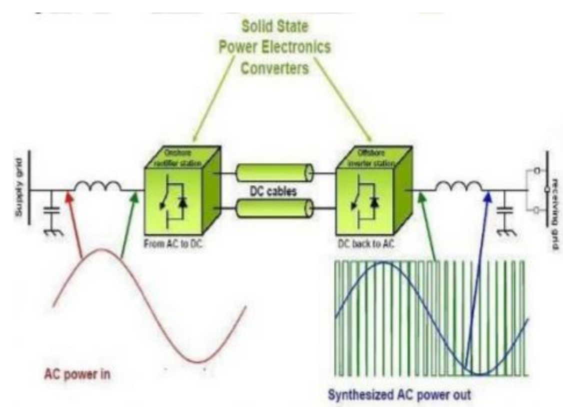

Fig. 3: HVDC Light model [1]

A. Comparison Between HVDC and HVDC Light

Conventional HVDC	HVDC light
Thyristor valve	IGBT valves
Converter transformer connects connection valve and AC grid.	Series reactor and transformer connects connection valve and AC grid.
50% filtering and reactive compensation in filters and shunt capacitor.	Only small filters are required for filtering and reactive power compensation.
DC current smoothing by smoothing reactor and DC filter.	Dc current smoothing by DC capacitors.

Fig. 4: Comparison between HVDC and HVDC Light [1]

III. POWER FLOW ANALYSIS

A bus is a node at which one or many lines, one or many loads and generators are connected. In a power system each node or bus is associated with 4 quantities, such as magnitude of voltage, phage angle of voltage, active or true power and reactive power in load flow problem two out of these 4 quantities are specified and remaining 2 are required to be determined through the solution of equation. Depending on the quantities that have been specified, the buses are classified into 3 categories.

- Load bus
- Generator bus or voltage controlled bus
- Slack (swing) bus

A. Case 1: 5 Bus Book Case Without HVDC Light

A MATLAB program is written to calculate the bus voltages ,active power and reactive power and voltage phase at every bus in the system for every iteration.The input data for the program is given.

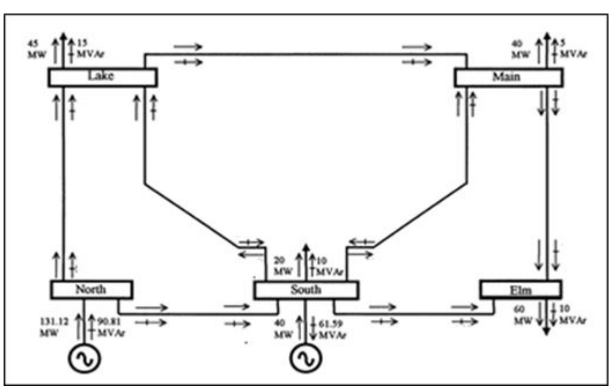

Fig. 5: 5 Bus Book Case without HVDC Light [6]

Information	North	South	Lake	Main	Elm
|V| (p.u.)	1.06	1.00	0.987	0.984	0.972
Θ (degrees)	0.00	-2.06	-4.64	-4.96	-5.76
P (p.u.)	1.311	0.200	-0.450	-0.400	-0.600
ΔP (p.u.)		-1.64e-13	-4.51e-14	-1.88e-14	2.63e-14
Q (p.u.)	0.908	-0.716	-0.150	-0.050	-0.100
ΔQ (p.u.)		0.616	-1.613e-13	-3.393e-14	7.780e-14

Fig. 6: Iterative Result of 5 Bus Book Case without HVDC Light

By doing iterative analysis up-to 7 iteration the graphical analysis of 5 bus without HVDC light model shows that the bus with less negative phase angle and more voltage then other buses power flow from that bus to another buses the voltage profile at south bus remain constant and its reactive power consumption remain constant from iteration 2 to onward.

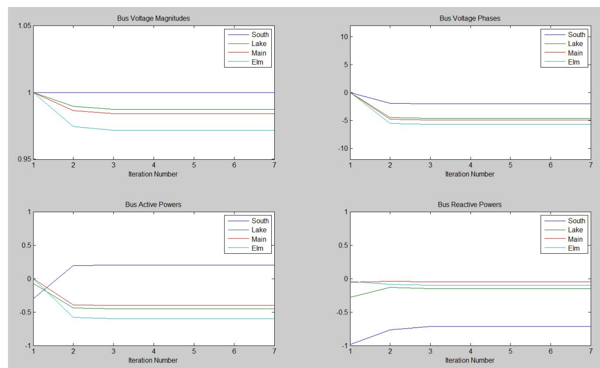

Fig. 7: Graphical analysis of bus Voltage vs Phase & Active vs Reactive power

B. Case 2: 5 Bus Book Case With HVDC Light

Rectifier is connected to Lake using Z_r. Rectifier is modeled as a PQ node to draw desired power P_{reg} = 0.25 p.u. from Lake. The voltage of Lake node $|V_l|$ is regulated at 1 p.u.

$$V_R = |V_R|(\cos\theta_R + j\sin\theta_R)$$

Inverter is connected to Main using Z_i. Inverter is modeled as a PV node to deliver desired active power P_{reg} = 0.25 p.u. and absorb desired reactive power Q_{reg} = -0.06 p.u.

$$V_i = |V_i|(\cos\theta_i + j\sin\theta_i)$$

The Converters are lossless hence no active power is lost between the Rectifier and Inverter.

$$R_e = V_r.I_l + V_i.I_m = 0$$

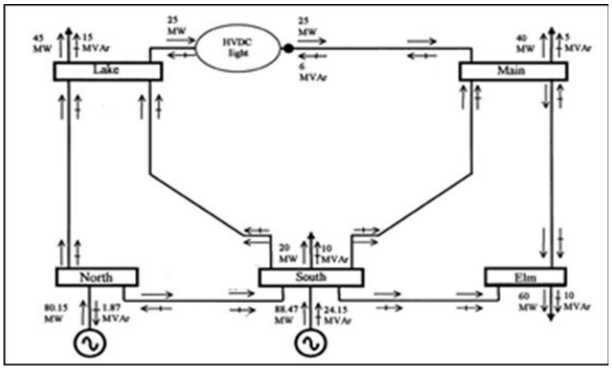

Fig. 8: 5 Bus Book Case with HVDC Light [6]

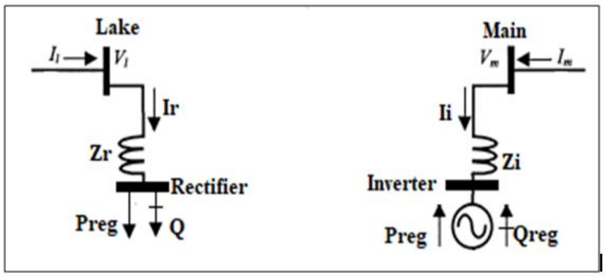

Fig. 9: Equivalent HVDC Light model between node L & M

The State Variables are the Rectifier phase angle and Inverter Voltage Magnitude. The Rectifier phase angle and Inverter Voltage Magnitude are updated after every iteration:

$$\theta_r^{n+1} = \theta_r^n + \Delta\theta_r^n$$

$$|V_l|^{r+1} = |V_l|^r + \Delta|V_i|^r$$

Information	North	South	Lake	Main	Elm	Rectifier	Inverter
|V| (p.u.)	1.036	1.029	1.000	1.003	0.998	1.005	1.006
Θ (degrees)	0.00	-1.41	-4.64	-3.55	-4.72	6.20	-2.50
P (p.u.)	0.7978	0.6789	-0.4397	-0.400	-0.600	-0.251	0.250
ΔP (p.u.)		0.0058	-0.0103	-1.44e-15	-1.22e-15	0.00104	4.44e-16
Q (p.u.)	-0.029	0.1736	-0.120	-0.050	-0.100	-0.031	-0.06
ΔQ (p.u.)		-0.2736	-0.0302	-8.17e-15	4.96e-15	0.0305	2.28e-15

Fig. 10: Iterative Result of 5 Bus Book Case with HVDC Light

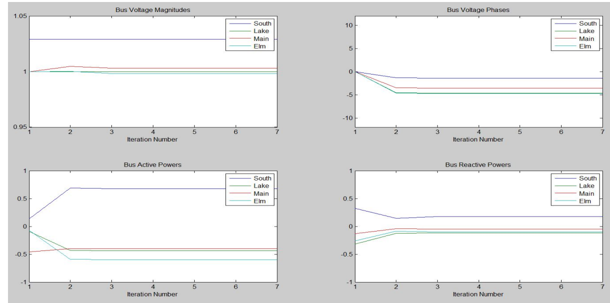

Fig. 11: Graphical analysis of bus Voltage vs Phase & Active vs Reactive power

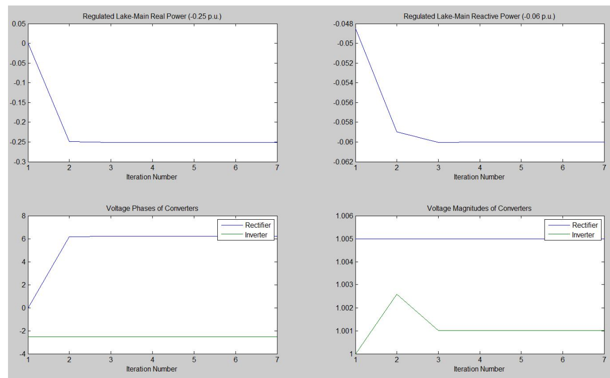

Fig. 12: Magnitude of voltage & phase of converters

C. Case 3: IEEE 14 Bus System without HVDC Light

The IEEE 14 bus system is simulated for voltages ,active and reactive powers at each bus. The standard IEEE 14 bus system is shown in figure. MATLAB program is used for IEEE 14 bus system with standard IEEE 14 bus system data. After simulating the program ,it displays results rectifier real power, rectifier voltage phase ,Inverter Reactive powers and Inverter voltage magnitude.

The system consists of 14 buses, 2 generators, 3 synchronous condensers, 11 loads, three transformers and 3 phase shifters. The Generators and Synchronous condensers can deliver active and reactive powers for regulating constant 1.06 p.u. voltage magnitudes at their respective buses.

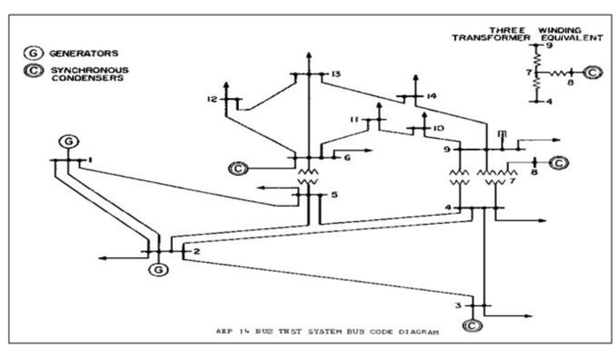

Fig. 13: IEEE 14 Bus System without HVDC Light

Information	1	2	3	4	5	6	7	8	9	10	11	12	13	14
|V| (p.u.)	1.060	1.060	1.060	1.048	1.048	1.060	1.040	1.060	1.024	1.024	1.039	1.049	1.043	1.021
Θ (degrees)	0.00	-6.44	-15.8	-13.1	-11.2	-17.1	-16.3	-16.3	-18.1	-18.5	-18.1	-18.6	-18.9	-20.3
P (p.u.)	2.44	0.183	-0.942	-0.478	-0.076	-0.112	0	0	-0.295	-0.090	-0.035	-0.061	-0.135	-0.149
ΔP (p.u.)		6e-16	-3e-15	-4e-15	5e-16	2e-15	-8e-16	1e-16	-6e-15	1e-15	-5e-16	-6e-16	-3e-16	4e-16
Q (p.u.)	0.213	0.309	0.119	0.039	-0.016	0.274	0	0.123	-0.166	-0.058	-0.018	-0.016	-0.058	-0.050
ΔQ (p.u.)		-0.01	-0.075	4e-15	-6e-15	-0.227	0	0.050	3e-15	-1e-15	6e-16	9e-16	-1e-15	-2e-15

Fig. 14: Iterative Result of IEEE 14 Bus System without HVDC Light

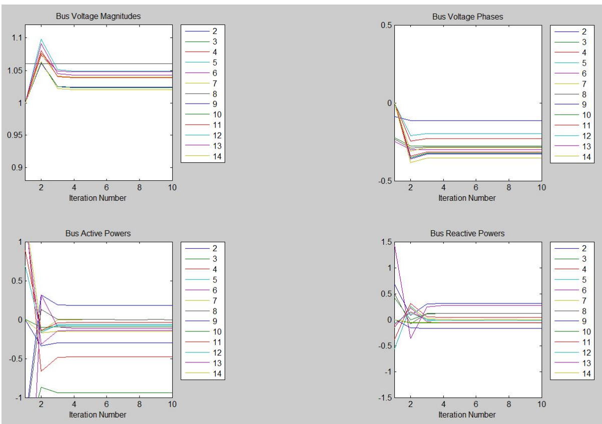

Fig. 15: Graphical analysis between Bus Voltage,Phase,Active & Reactive power

D. Case 4: IEEE 14 Bus System with HVDC Light

Rectifier is connected to bus 13 using Z_r. Rectifier is modeled as a PQ node to draw desired power P_{reg} =0.25 p.u. from Lake. The voltage of bus 13 is regulated at 1.06 p.u. Rectifier is connected to bus 13 using Z_r. Rectifier is modeled as a PQ node to draw desired power P_{reg} =0.25 p.u. from Lake. The voltage of bus 13 is regulated at 1.06 p.u.

$$V_R = |V_R|(\cos\theta_R + j\sin\theta_R)$$

Inverter is connected to bus 14 using Z_i. Inverter is modeled as a PV node to deliver desired active power P_{reg} = 0.25 p.u. and absorb desired reactive power Q_{reg} = -0.06 p.u.

$$V_i = |V_i|(\cos\theta_i + j\sin\theta_i)$$

The Converters are lossless hence no active power is lost between the Rectifier and Inverter.

$$R_e = V_r.I_l + V_i.I_m = 0$$

The State Variables are the Rectifier phase angle and Inverter Voltage Magnitude. The Rectifier phase angle and Inverter Voltage Magnitude are updated after every iteration:

$$\theta_r^{n+1} = \theta_r^n + \Delta\theta_r^n$$
$$|V_l|^{r+1} = |V_l|^r + \Delta|V_i|^r$$

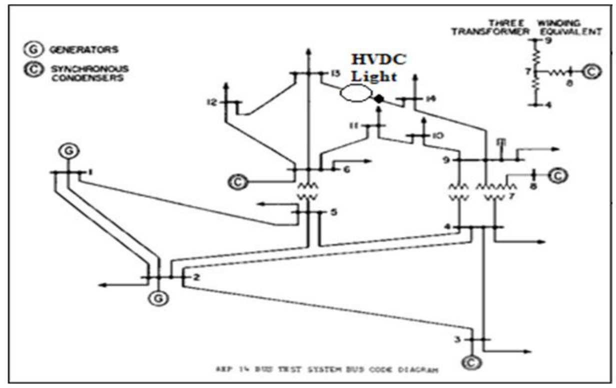

Fig. 16: IEEE 14 Bus System with HVDC Light

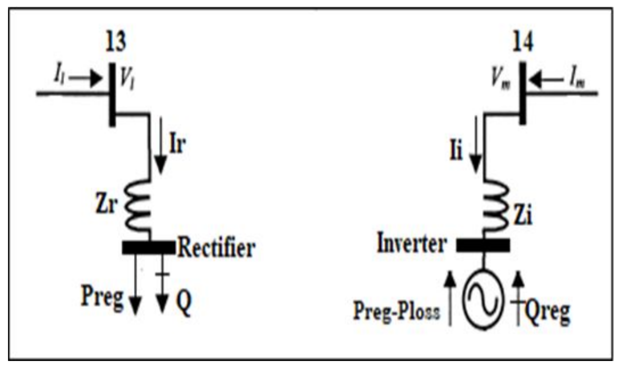

Fig. 17: HVDC Light connect between bus 13 & 14

Information	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Rectifier	Inverter
|V| (p.u.)	1.060	1.060	1.060	1.048	1.048	1.060	1.034	1.060	1.011	1.013	1.033	1.056	1.060	0.965	1.060	1.007
Θ (degrees)	0.00	-5.85	-14.8	-12.1	-10.6	-18.1	-14.7	-14.7	-16.1	-17.0	-17.8	-20.3	-21.5	-13.9	-21.6	-13.2
P (p.u.)	2.20	0.183	-0.942	-0.478	-0.076	-0.112	0	0	-0.295	-0.090	-0.035	-0.061	-0.135	-0.149	-0.250	0.250
ΔP (p.u.)		-8e-10	-1e-9	1e-9	-6e-10	-2e-5	-6e-9	-1e-9	2e-9	5e-10	6e-10	-4e-6	1e-5	-3e-7	2e-5	1e-7
Q (p.u.)	0.126	0.182	0.080	0.039	-0.016	0.195	0	0.157	-0.166	-0.058	-0.018	-0.018	0.020	-0.050	0.0003	-0.060
ΔQ (p.u.)		0.211	0.270	1e-9	1e-8	-0.291	1.5e-7	-0.116	-2e-8	-9e-9	4e-8	2e-4	-0.01	-8e-8	-2e-4	-1e-8

Fig. 18: Iterative Result IEEE 14 Bus System with HVDC Light

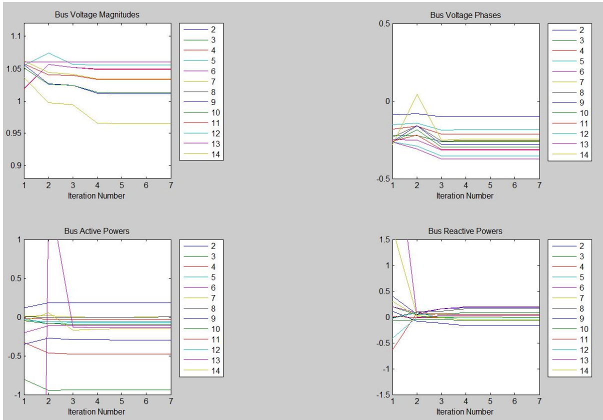

Fig. 19: Graphical analysis between Bus Voltage,Phase,Active & Reactive power

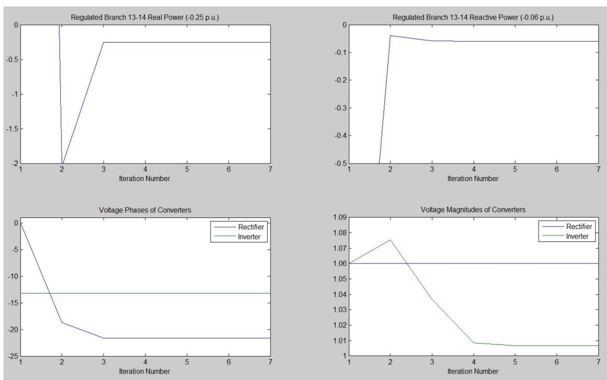

Fig. 20: IEEE 14 Bus System with HVDC Light

E. Case 5: IEEE 14 Bus System with New HVDC Light Model

The new HVDC Light Model is different from the Book HVDC Light Model in that the Converters are connected using DC cables which contribute to active power loss. The loss is dependent on the constant DC voltage level and DC cable resistance.

Rectifier is connected to bus 13 using Z_r. Rectifier is

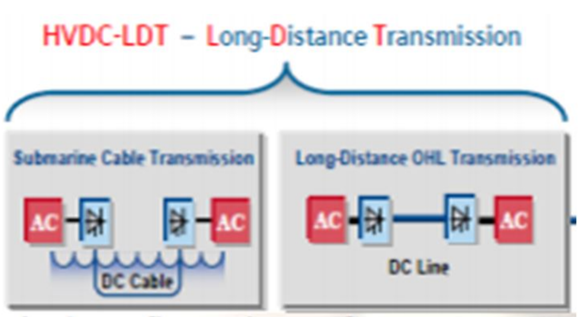

Fig. 21: IEEE 14 Bus System with New HVDC Light Model

modeled as a PQ node to draw desired power P_{reg} =0.25 p.u. from Lake. The voltage of bus 13 is regulated at 1.06 p.u.

$$V_R = |V_R|(\cos\theta_R + j\sin\theta_R)$$

Inverter is connected to bus 14 using Z_i. Inverter is modeled as a PV node to absorb desired reactive power Q_{reg} =-0.06 p.u.

$$V_i = |V_i|(\cos\theta_i + j\sin\theta_i)$$

Power is lost between Rectifier and Inverter due to the DC cable.

The State Variables are the Rectifier phase angle and Inverter Voltage Magnitude. The Rectifier phase angle and Inverter Voltage Magnitude are updated after every iteration:

$$\theta_r^{n+1} = \theta_r^n + \Delta\theta_r^n$$

$$|V_l|^{r+1} = |V_l|^r + \Delta|V_i|^r$$

Information	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Rectifier	Inverter
|V| (p.u.)	1.060	1.060	1.060	1.048	1.049	1.060	1.034	1.060	1.011	1.013	1.033	1.056	1.060	0.965	1.060	0.999
Θ (degrees)	0.00	-5.97	-15.1	-12.5	-10.9	-18.5	-15.3	-15.2	-16.8	-17.7	-18.3	-20.7	-21.9	-15.8	-21.9	-15.0
P (p.u.)	2.25	0.183	-0.942	-0.478	-0.076	-0.112	0	0	-0.295	-0.090	-0.035	-0.061	-0.135	-0.149	-0.250	0.200
ΔP (p.u.)		-1e-9	3e-10	4e-9	-1e-10	-2e-4	-5e-9	-9e-10	-9e-11	3e-10	4e-10	-3e-5	8e-5	-2e-7	1e-4	1e-7
Q (p.u.)	0.133	0.192	0.083	0.039	-0.016	0.198	0	0.158	-0.166	-0.058	-0.018	-0.018	0.020	-0.050	0.0003	-0.060
ΔQ (p.u.)		0.105	0.039	5e-8	2e-9	-0.151	1e-7	0.016	-2e-8	-1e-8	3e-8	0.002	-0.078	-7e-8	-2e-4	7e-9

Fig. 22: Iterative Result IEEE 14 Bus System with New HVDC Light Model

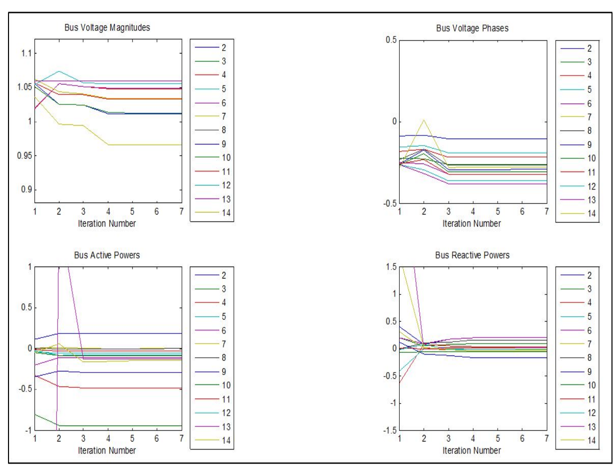

Fig. 23: Graphical analysis between Bus Voltage,Phase,Active & Reactive power

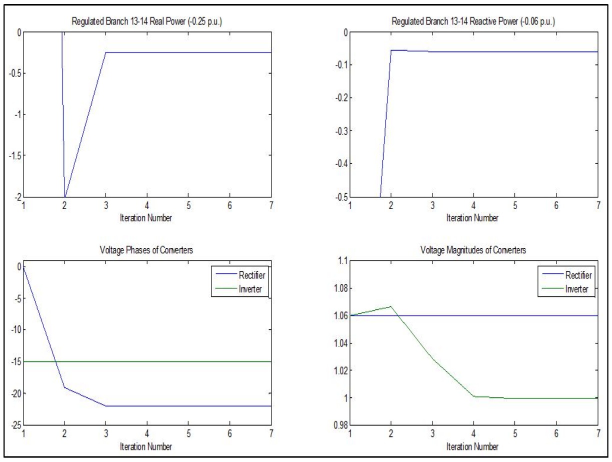

Fig. 24: Result IEEE 14 Bus System with New HVDC Light Model

IV. Conclusion

This System when implemented in the power system will minimize transmission loses with optimum system security for economic operation. In this paper, we analyze that how voltage profile will improve by using HVDC Light on IEEE 14 bus system model and 5 bus system model. This is verified by using the MATLAB program for 5 bus sample system and 14 bus system. Before implementing this model between specific buses we saw that the voltage profile at those buses that far away from source bus experience voltage dip due to excess of reactive power consumption. By applying these model on 5 & 14 bus system we saw that voltage profile considerably improve and their associated phase angle are become less negative. Also the reactive power consumption improved.

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