

Power Flow Analysis of System with HVDC Link

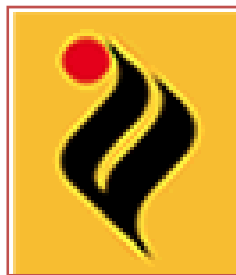
*Thesis submitted in partial fulfillment of the requirements for the award
of the degree of*

MASTER OF ENGINEERING in POWER SYSTEMS & ELECTRIC DRIVES

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CERTIFICATE

I hereby declare that the Thesis entitled “**Power Flow Analysis of AC System with HVDC Link**” is an authentic record of my own work carried out as the requirements for the award of the degree of M.E. (Power Systems & Electric Drives) at Thapar University, Patiala, under the guidance of **Dr. Sanjay K. Jain**, Associate Professor, EIED.


The matter presented in this Thesis has not been submitted for the award of any other degree of this or any other university.


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ABSTRACT

High Voltage Direct Current (HVDC) technology has made considerable advancements in recent years. The HVDC system has been studied to understand HVDC components, their advantages over the conventional ac transmission systems and their implementation with transmission system.

HVDC transmission has been an integral part of various power system networks. The power industry are demanding stronger trend towards supplying electric power of higher quality by improving the system security. The power flow analysis is very valuable for setting the proper protection devices to insure the security of the system. This analysis is an important tool for deciding stable operating conditions, control of power system and the future planning of power systems.

The main objective of the power flow analysis is to determine the steady state operating characteristics of the power generation/transmission system for a given set of bus loads. The main motivation of the work is to model a DC link and integrate it with the AC systems and to carry out power flow analysis using Newton Raphson method in the MATLAB environment. The performance has been studied for 9-Bus, 14-Bus and 11-Bus systems comprising HVDC link(s). The 14-bus system has been analyzed for two HVDC links as well whereas one HVDC link is assumed in other systems.

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CHAPTER-1

INTRODUCTION

1.1 OVERVIEW

Electric power transmission was originally developed with direct current. The availability of transformers and the development and of induction motors at the beginning of the 20th Century, led to greater appeal and use of AC transmission. The research and development on multi-electrode grid controlled mercury arc valve for high powers and voltages was carried out in 1929. Their use in conversion processes for transmission and frequency changing was carried out in 1930's. DC transmission now became practical when long distances were to be covered or where cables were required. After the Second World War, the research on HVDC got stimulated, particularly in Sweden and in Russia. In 1950, a 116 km experimental transmission line was commissioned from Moscow to Kasira at 200 kV.

The first commercial HVDC line built in 1954 was a 98 km submarine cable with ground return between the island of Gotland and the Swedish mainland. Thyristors were applied to DC transmission in the late 1960's and solid state valves became a reality. In 1969, a contract for the Eel River DC link in Canada was awarded as the first application of solid state valves for HVDC transmission. Today, the highest functional DC voltage for DC transmission is ± 600 kV for the 785 km transmission line of the Itaipu scheme in Brazil.

DC transmission is now an integral part of the delivery of electricity in many countries throughout the world. In view of rapid growth in demand and supply of electricity, electric power system is becoming increasingly large and more complex. Moreover, regular electric supply is the sheer necessity for growing industry and other fields of life. The power industry planners are demanding stronger trend towards supplying electric power of higher quality by improving the system security and its impact on environment in parallel with pursuit of economy. In real life situation, the criterion of perfection is never met, because there are deviations between the model and reality. Load flow and state estimation analysis are important tools for deciding the stable operation and control of power system as well as future planning of power systems.[1,2]

High voltage AC-DC technology has made considerable advances in recent years. Engineers are now considering DC multi-terminal network as a feasible option. Therefore,

the load flow and state estimation techniques are extended to deal with such mixed AC-DC systems. Multi-terminal DC network integrated into an existing system can improve AC equipment loading and stability, participate in load frequency control (LFC) and voltage regulation, increase interchange capacity, limit short circuit capacity and contribute to the economy of electric power transmission.[3]

Multi-terminal DC network as well as two-terminal DC links require communication between converter terminals and control of DC system start-up and shutdown, coordination of operating set points, and for DC system structure changes such as line or terminal outages. Link or meshed DC multi-terminal network integrated to AC systems is feasible and can be advantageous in certain applications such as bulk power transmission, AC networks interconnection and reinforcing AC networks.

The main objective of load flow calculations is to determine the steady state operating characteristics of the power generation/transmission system for a given set of bus bar loads. The load flow calculations provide voltages, power flows and power losses for a specified power system subject to the regulating capabilities of the generators, condensers and on-load tap changing transformers as well as the net power exchange between the individual power systems.

This information is essential for continuously evaluating the operating performance of a power system and analyzing the effectiveness of alternative plans for system expansion to meet the increasing load demand. The load flow studies are also necessary for the power system stability assessment, contingency evaluation and economic operation. The significance of these studies has become more relevant in modern times due to the control and operation of the interconnected large size power systems in a real-time environment. Imposing a DC network between AC generators and load or between two AC systems offer several technical and economical advantages. The growing number of schemes in existence and under consideration demands corresponding modeling facilities for planning and operational purposes.[4,5]

In recent years, great advantages have been made in converter technology which has resulted in cheaper and more reliable power utilization. The basic load flow has to be substantially modified to be capable of modeling the operating state of the combined AC and

DC systems under the specified conditions of load, generation and DC system control strategies.

Figure 1.1 shown is an example of a general HVDC system.[6] As shown it consist of an HVDC link, converter bridges, converter transformers, AC side filters, DC filters, DC line and bus arresters, surge capacitors and reactors. Converters unit employed may be 6-pulse bridge converter or 12-pulse bridge converters. Converter transformer employed to adapt the ac voltage level to the Dc voltage level. Filters are employed to reduce the harmonic content. During the conversion process of reactive power is absorbed, that reactive power is compensated by filters employed in the system. Capacitor banks also helps in improving reactive power level. HVDC converters create harmonics in all operational modes. Such harmonics can create disturbances in telecommunication systems. Therefore, specially designed DC filters are used in order to reduce these disturbances.

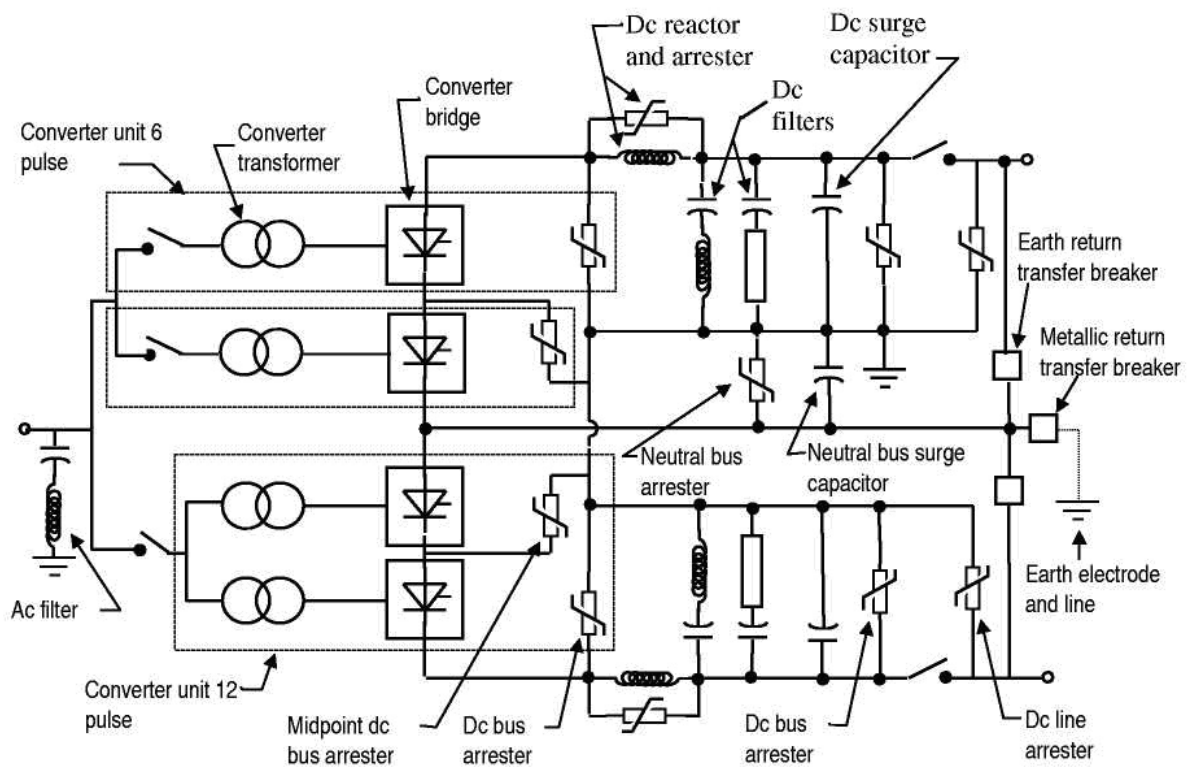


Figure 1.1 Example of HVDC substation

1.2 LITERATURE REVIEW

The studies of HVDC systems, their advantages and analysis of load flow in HVDC systems and their implementation is much developed here the literature review on these aspects is briefly summarized as:

Rudervall and Charpentier discussed the HVDC systems from a design, construction, operation and maintenance points of view. This work includes an economic and financial comparison of HVDC system with that of an AC system.

Panosyan and Oswald presented the model of a two-terminal HVDC link and its integration into the well-known Newton-Raphson method for the load flow analysis taking into account the control strategies of the HVDC converter stations. It is suggested that the simplest way of integrating a DC link into the AC load flow is by representing it by constant active and reactive power injections at the two terminal buses in the AC systems. Thus the two terminal AC- DC buses are represented as a PQ-bus with a constant voltage independent active and reactive power.

Haileselassie and Uhlen proposed a numerical iteration method based upon the Newton-Raphson approximation for analyzing power flow in multi-terminal HVDC networks. The method was tested to analyze the power flow of a five terminal HVDC grid. The method suggested that even with poor initial guesses of the unknown node voltages, the iterative method gives a convergent solution of the required error margin within few iteration steps.

Veilleux and Ooi explored the development of a new type of DC grid. The DC grid has less degree of freedom than an AC grid which restricts its power flow control ability. To overcome this situation, an auxiliary DC voltage controller that would vary the voltage on a DC line can be inserted to provide additional degrees of control freedom.

Mobarak presented the well-known Newton-Raphson method for the load flow analysis of system consisting of HVDC link. The original NR method is modified to achieve compatibility for AC/DC systems with integrated DC links in the AC network. The modified Jacobian equation includes the DC real and reactive power at the AC/DC buses, and their dependency on the AC system variables.

Hingorani and Mountford presented a suitable method by which HVDC trunk lines are simulated for the purpose of load-flow analysis by digital. The representation of the DC link in an AC system is best achieved by equivalent current generators at the AC system nodes containing the convertor terminals. The relationship between the injected currents and the voltages at the nodes is defined by the proposed routine, which is accurate and fully equipped with HVDC system controls.

Mustafa and Kadir proposed a method dealing with the development of load flow solution for a HVDC link in a power system. The load flow solution was based on the fast decoupled method which needs some iteration to obtain the result. The Variables of the direct current link which have been chosen for simulation are the converter terminal DC voltages, converter transformer tap ratios, firing angle of the rectifier and current in the HVDC link.

Sanghavi and Banerjee suggested a sequential approach for performing the load flow analysis of an integrated AC-DC power system. In this approach a simplified model of the DC link has been developed and the means of integrating the link equation with a standard AC load flow program has been explained. In this model minimum amount of modifications have been made with a standard AC load flow program.

Mahseredjian and Mukhedkar proposed a sequential AC-DC load-flow method for parallel multi terminal dc networks. The AC-DC load-flow method offers a large variety of converter controls in combination with discrete tap-step, fixed or variable tap transformers. The algorithm is designed to overcome difficult primary solution or experimented user control scheduling for a dc network. Single current, power and voltage controls can be used to obtain a primary dc load-flow solution and double controls can be used to adjust the final solution.

Marsafawy and Mathur proposed a new method for the load-flow calculations of integrated AC/DC systems. They proposed use of fast decoupled load flow method, which handles all AC/DC equations simultaneously, and fully exploits the sparsity techniques. They have shown application of the technique on two systems, one with a point to-point DC transmission and the other with a 3-terminal mesh HVDC sub-system. It was a fast technique for load-flow studies of an integrated AC/DC system.

1.3 OBJECTIVE OF THE WORK

The objective of the present work is to study HVDC systems and to analyze load flow analysis of system having HVDC link as well. The objective is to develop an algorithm to solve the HVDC link power system load flow and to test that algorithm on the IEEE test system. For the integration of HVDC link with an AC power system, the direct current link Variables that have been chosen for simulation are the converter terminal DC voltages, converter transformer tap ratios, firing angle of the rectifier and current in the HVDC link.

1.4 ORGANISATION OF THESIS

The work carried out in this thesis has been summarized in four chapters. The **Chapter-1** deliberates the overview of the topic, brief literature review, objectives of the work and organization of thesis. The **Chapter-2** discusses about HVDC transmission, its components, and advantages over HVAC. In **Chapter-3** load flow analysis in HVDC has been discussed. DC link has been modeled and its integration with AC load flow has been carried out in this chapter. The load flow results on various bus systems are presented **Chapter-4**. The conclusion and scope of future work have been detailed in **Chapter-5**.

CHAPTER-2

HVDC SYSTEM

2.1 GENERAL

Electric power transmission was originally developed with direct current. DC power at low voltage could not be transmitted over long distances, thus giving rise to high voltage alternating current (AC) electrical systems. High voltage (in either AC or DC electrical power transmission applications) is used for electric power transmission to reduce the energy lost in the resistance of the wires as for a given quantity of power transmitted and size of conductor, doubling the voltage will deliver the same power at only half the current. Since the power lost as heat in the wires is proportional to the square of the current, but does not depend in any major way on the voltage delivered by the power line, doubling the voltage in a power system reduces the line-loss loss per unit of electrical power delivered.

Since DC transmission at higher voltage levels results into lower losses for larger distances as compared to AC transmission so High Voltage Direct Current transmission is preferable over large distances. HVDC transmission has been in use for more than 50 years. It has proved to be a reliable and valuable transmission media for electrical energy and has a number of technical advantages compared with HVAC transmission. Nonetheless, a comprehensive HVDC/HVAC system planning approach is not commonly found within utilities, and therefore full advantage is not being taken of the HVDC technology.

Recent developments in energy policies and stronger environmental lobbies have a significant impact on the design and construction of electrical power transmission networks, and could provide a number of opportunities for HVDC transmission. However, HVDC transmission is perceived to be expensive, difficult to integrate in an AC network, to require highly skilled personnel to operate and maintain, and to have high power losses. High Voltage Direct Current (HVDC) transmission finally proved to be technically feasible. The world's first commercial HVDC transmission link, was built in 1954 between the Swedish mainland and the island of Gotland, with a rating of 20 MW, 200 A and 100 kV.[7-12]

2.2 ADVANTAGES OF HVDC OVER HVAC SYSTEM

- HVDC transmission has 30-50% less transmission loss than comparable alternating current overhead lines.
- Generally, given the same width of the cable run, 30-40% more energy transmission is possible than with conventional overhead lines carrying alternating current.
- Transmission losses are lower than for AC voltage. DC voltage amounts to several hundred thousand volts. The higher the voltage, the lower the transmission losses are, and the more electricity can be transmitted via the line.
- Generally, an HVDC transmission link has two poles (and also two lines between them) over which half of the electricity is transmitted. If one pole or line were to fail, half of the remaining power would still be available.
- Less corona loss and radio interference, especially in foul weather, for a certain conductor diameter and rms voltage.
- Long undersea cables have a high capacitance. While this has minimal effect for DC transmission, the current required to charge and discharge the capacitance of the cable causes additional I^2R power losses when the cable is carrying AC. In addition, AC power is lost to dielectric losses.
- HVDC can carry more power per conductor, because for a given power rating the constant voltage in a DC line is lower than the peak voltage in an AC line. This voltage determines the insulation thickness and conductor spacing. This allows existing transmission line corridors to be used to carry more power into an area of high power consumption, which can lower costs.
- Because HVDC allows power transmission between unsynchronized AC distribution systems, it can help increase system stability, by preventing cascading failures from propagating from one part of a wider power transmission grid to another. Changes in load that would cause portions of an AC network to become unsynchronized and separate would not similarly affect a DC link, and the power flow through the DC link would tend to stabilize the AC network. The magnitude and direction of power

flow through a DC link can be directly commanded, and changed as needed to support the AC networks at either end of the DC link. This has caused many power system operators to contemplate wider use of HVDC technology for its stability benefits alone.

- Copper saving is also economical. Skin effect and proximity effect can be completely eliminated.
- Provide a means to control the magnitude and directions of the electric power flow. The power flow over an HVDC line can be controlled by adjusting the AC system voltages at the converter terminals. This provides very fast control of power flow which allows improvements in system stability. Also the direction of power flow can be changed very quickly.
- An HVDC link does not increase the short circuit currents at the connecting points. This means that it will not be necessary to change the circuit breakers in the existing networks.
- When there is the need to transmit power across long distances of water where there is no method of providing the intermediate voltage compensation that HVAC requires.
- When there is a need to connect two existing systems in asynchronous manner to prevent losses of a block of generation in one system from causing transmission overloads in the other system if connected with HVAC.[13,14]

2.3 BREAK EVEN DISTANCE IN HVDC

Comparisons are needed to highlight the cost comparison between high voltage AC and HVDC systems. Thyristor based HVDC system versus high voltage AC system is considered here. The investment costs for HVDC converter stations are higher than for high voltage AC substations. On the other hand, the costs of transmission medium (overhead lines and cables), land acquisition/right-of-way costs are lower in the HVDC case. Moreover, the operation and maintenance costs are lower in the HVDC case.[19] Initial loss levels are higher in the HVDC system, but they do not vary with distance. In contrast, loss levels

increase with distance in a high voltage AC system. Figure 2.1 shows the cost breakdown (shown with and without considering losses).

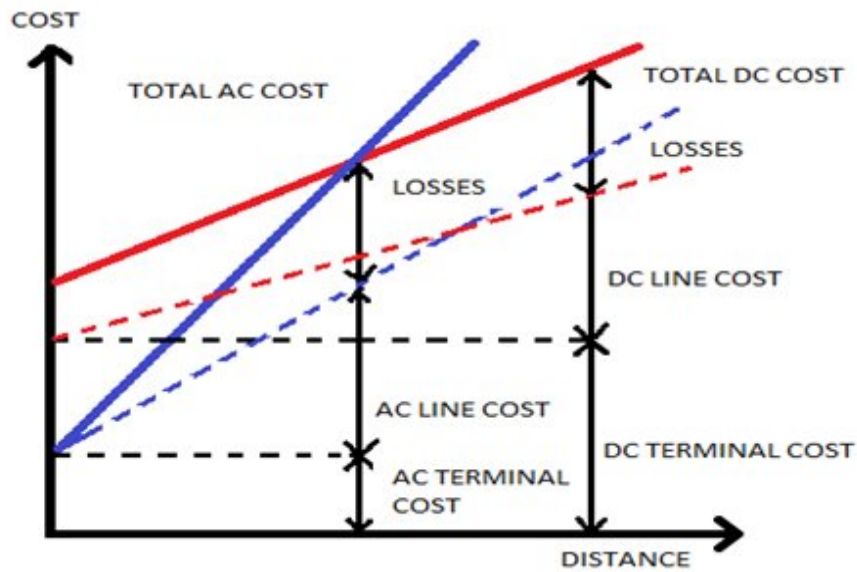


Figure 2.1 Variation of cost with distance

2.4 COMPONENTS OF HVDC SYSTEM

The most relevant components that comprise a HVDC system are the following as shown in Figure 2.2:

1. Converter Transformer.
2. Rectifier.
3. Inverter.
4. AC filter.
5. DC filter.

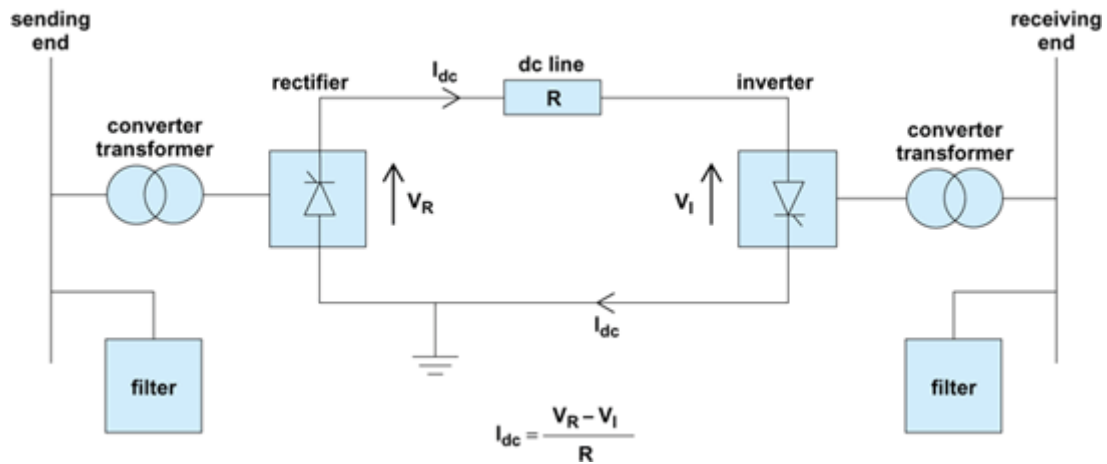


Figure 2.2 Schematic arrangements of the components of HVDC system

THE CONVERTER STATION

The converter stations at each end are replica's of each other and therefore consists of all the needed equipment for going from AC to DC or vice versa. The main components of a converter station are:

Converter Transformers: The converter transformers adapt the AC voltage level to the DC voltage level and they contribute to the commutation reactance. Usually they are of the single phase three winding type, but depending on the transportation requirements and the rated power, they can be arranged in other ways also.

Thyristor valves: The thyristor valves can be build-up in different ways depending on the application and manufacturer. However, the most common way of arranging the thyristor valves is in a twelve-pulse group with three quadruple valves. Each single thyristor valve consists of a certain amount of series connected thyristors with their auxiliary circuits. All communication between the control equipment at earth potential and each thyristor at high potential is done with fiber optics.

VSC valves: The VSC converter consists of two level or multilevel converter, phase-reactors and AC filters. Each single valve in the converter bridge is built up with a certain number of series connected IGBTs together with their auxiliary electronics. VSC valves, control equipment and cooling equipment would be in enclosures (such as standard shipping containers) which make transport and installation very easy. All modern HVDC valves are water-cooled and air insulated.

AC Filters and Capacitor Banks: On the AC side of a 12-pulse HVDC converter, current harmonics of the order of 11, 13, 23, 25 and higher are generated. Filters are installed in order to limit the amount of harmonics to the level required by the network. In the conversion process the converter consumes reactive power which is compensated in part by the filter banks and the rest by capacitor banks. In the case of the CCC the reactive power is compensated by the series capacitors installed in series between the converter valves and the converter transformer.

The elimination of switched reactive power compensation equipment simplify the AC switchyard and minimize the number of circuit-breakers needed, which will reduce the area required for an HVDC station built with CCC. With VSC converters there is no need to compensate any reactive power consumed by the converter itself and the current harmonics on the AC side are related directly to the PWM frequency. Therefore the amount of filters in this type of converters is reduced dramatically compared with natural commutated converters.

DC filters: HVDC converters create harmonics in all operational modes. Such harmonics can create disturbances in telecommunication systems. Therefore, specially designed DC filters are used in order to reduce the disturbances. Usually no filters are needed for pure cable transmissions as well as for the Back-to-Back HVDC stations. However, it is necessary to install DC filters if an OH line is used in part or all the transmission system. The filters needed to take care of the harmonics generated on the DC end, are usually considerably smaller and less expensive than the filters on the AC side. The modern DC filters are the active DC filters. In these filters the passive part is reduced to a minimum and modern power electronics is used to measure, invert and re-inject the harmonics, thus rendering the filtering very effective.

Transmission medium: For bulk power transmission over land, the most frequent transmission medium used is the overhead line. This overhead line is normally bipolar, i.e. two conductors with different polarity. HVDC cables are normally used for submarine transmission. The most common types of cables are the solid and the oil-filled ones. The solid type is in many cases the most economic one. Its insulation consists of paper tapes impregnated with high viscosity oil. No length limitation exists for this type and designs are today available for depths of about 1000 m. The self-contained oil-filled cable is completely filled with low viscosity oil and always works under pressure. The maximum length for this cable type seems to be around 60 km.[20] The development of new power cable technologies

has accelerated in recent years and today a new HVDC cable is available for HVDC underground or submarine power transmissions. This new HVDC cable is made of extruded polyethylene and is used in VSC based HVDC systems.

2.5 REASONS FOR CHOOSING HVDC

There are many different reasons for choosing HVDC transmission. A few of the reasons in selected projects are:

- In Itaipu, Brazil, HVDC was chosen to supply 50Hz power into a 60 Hz system; and to economically transmit large amount of hydro power (6300 MW) over large distances (800km).
- In Leyte-Luzon Project in Philippines, HVDC was chosen to enable supply of bulk geothermal power across an island interconnection, and to improve stability to the Manila AC network.[21]
- In Queensland, Australia, HVDC was chosen in an ITP to interconnect two independent grids(of New South Wales and Queensland) to enable electricity trading between the two systems(including change of direction of power flow) ensure very low environmental impact and reduce construction time.
- In Rihand-Delhi Project in India, HVDC was chosen to transmit bulk (thermal) power (1500 MW) to Delhi, to ensure: minimum losses, least amount right-of-way, and better stability and control.
- In Garabi, an independent transmission project (ITP) transferring power from Argentina to Brazil, HVDC back-to-back system was chosen to ensure supply of 50 Hz bulk (1000MW) power to a 60 Hz system under a 20-year power supply contract.[22-26]
- In Gotland, Sweden, HVDC was chosen to connect a newly developed wind power site to the main city of Visby, in consideration of the environmental sensitivity of the project area (an archaeological and tourist area) and improve power quality.

CHAPTER-3

POWER FLOW ANALYSIS

3.1 GENERAL

Load flow study is an important tool involving numerical analysis applied to a power system. A power flow study usually uses simplified notation such as a one-line diagram and per-unit system and focuses on various forms of AC power (i.e. voltages, voltage angles, real power and reactive power). It analyzes the power systems in normal steady-state operation. There exist a number of software implementations of power flow studies. Load flow analysis is probably the most important of all network calculations since it concerns the network performance in its normal operating conditions. It is performed to investigate the magnitude and phase angle of the voltage at each bus and the real and reactive power flows in the system components.

Load flow analysis has a great importance in future expansion planning, in stability studies and in determining the best economical operation for existing systems. Also load flow results are very valuable for setting the proper protection devices to insure the security of the system. In order to perform a load flow study, full data must be provided about the studied system, such as connection diagram, parameters of transformers and lines, rated values of each equipment, and the assumed values of real and reactive power for each load.[27]

The goal of a power flow study is to obtain complete voltage angle and magnitude information for each bus in a power system for specified load and generator real power and voltage conditions. Once this information is known, real and reactive power flow on each branch as well as generator reactive power output can be analytically determined. Due to the nonlinear nature of this problem, numerical methods are employed to obtain a solution that is within an acceptable tolerance.

3.2 LOAD FLOW OF AC SYSTEM

In the load flow studies, the steady state power and reactive power supplied by a bus in a power network are expressed in terms of nonlinear algebraic equations. Through iterative methods we can obtain the voltage magnitudes and angles at each bus in the steady state. This is rather important as the magnitudes of the bus voltages are required to be held within a

specified limit. Once the bus voltage magnitudes and their angles are computed using the load flow, the real and reactive power flow through each line can be computed. Also based on the difference between power flow in the sending and receiving ends, the losses in a particular line can also be computed. Furthermore, from the line flow we can also determine the over and under load conditions.[28,29]

3.2.1 BUS CLASSIFICATION

Each bus in the system has four variables: voltage magnitude, voltage angle, real power and reactive power. During the operation of the power system, each bus has two known variables and two unknowns. Generally, the bus must be classified as one of the following bus types:

Slack or Swing Bus

This bus is considered as the reference bus. It must be connected to a generator of high rating relative to the other generators. During the operation, the voltage of this bus is always specified and remains constant in magnitude and angle. In addition to the generation assigned to it according to economic operation, this bus is responsible for supplying the losses of the system.

Generator or Voltage Controlled Bus

During the operation the voltage magnitude at this the bus is kept constant. Also, the active power supplied is kept constant at the value that satisfies the economic operation of the system. Most probably, this bus is connected to a generator where the voltage is controlled using the excitation and the power is controlled using the prime mover control. Sometimes, this bus is connected to a VAR device where the voltage can be controlled by varying the value of the injected VAR to the bus.

Load Bus

This bus is not connected to a generator so that neither its voltage nor its real power can be controlled. On the other hand, the load connected to this bus will change the active and reactive power at the bus in a random manner [30]. To solve the load flow problem we have to assume the complex power value (real and reactive) at this bus.

3.2.2 POWER FLOW IN AC SYSTEM

The solution to the power flow problem begins with identifying the known and unknown variables in the system. The known and unknown variables are dependent on the type of bus. A bus without any generators connected to it is called a Load Bus. With one exception, a bus with at least one generator connected to it is called a Generator Bus. The exception is one arbitrarily-selected bus that has a generator. This bus is referred to as the Slack Bus.

In the power flow problem, it is assumed that the real power P_D and reactive power Q_D at each Load Bus are known. For this reason, Load Buses are also known as PQ Buses. For Generator Buses, it is assumed that the real power generated P_G and the voltage magnitude $|V|$ is known. For the Slack Bus, it is assumed that the voltage magnitude $|V|$ and voltage phase δ are known. Therefore, for each Load Bus, both the voltage magnitude and angle are unknown and must be solved for these both unknowns. Similarly for each Generator Bus, the voltage angle and reactive power are unknowns and must be solved for these unknowns. There are no variables that must be solved for the Slack Bus.

Assuming a system having n buses, the injected current to the bus (node) k can be expressed as:

$$I_k = \sum_{n=1}^N Y_{kn} V_n \quad (3.1)$$

Where Y_{kn} is the proper element in the bus admittance matrix Y_{bus} and,

$$Y = |Y| \angle \theta, V = |V| \angle \delta$$

The complex power at k th bus is given as

$$S_k^* = V_k^* I_k = P_k - jQ_k \quad (3.2)$$

$$P_k - jQ_k = V_k^* \sum_{n=1}^N Y_{kn} V_n \quad (3.3)$$

$$P_k = |V_k| \left| \sum_{n=1}^N Y_{kn} \right| |V_n| \cos(\delta_n - \delta_k + \theta_{kn}) \quad (3.4)$$

$$Q_k = |V_k| \left| \sum_{n=1}^N Y_{kn} \right| |V_n| \sin(\delta_n - \delta_k + \theta_{kn}) \quad (3.5)$$

Where, P_k and Q_k are the active and reactive power injections at bus k respectively. Thus, at each bus there are two equations but four variables namely P , Q , δ and V . The Y 's and θ 's are known from network data. Actually, at each bus we have to specify two variables and solve for the remaining two unknowns. Thus, for an N bus system $2N$ equations are solved. These $2N$ equations are nonlinear equations as they involve products of variables as well as sine and cosine functions.[31]

3.2.3 NEWTON-RAPHSON METHOD FOR AC LOAD FLOW

The Newton-Raphson method is the most efficient load-flow algorithm. The basic (no approximations) Newton-Raphson algorithm is based on the formal application of a well-known algorithm for the solution of a set of simultaneous non-linear equations of the form:

$$[F(X)] = [0] \quad (3.6)$$

Where, $[F(x)]$ is a vector of functions: $f_1 \dots f_n$ in the variables $x_1 \dots x_n$.

The above expression does not equal zero until the Newton-Raphson process has converged (i.e., all the x 's have been found) and the iterations have to be performed, starting at some initial set of values x_1, x_2, \dots, x_n .

In the load flow problem the x 's are voltage magnitude and phase angle at all PQ buses and voltage phase angles at all PV buses i.e. angles at all buses except slack and $|V|$ for all load buses. The iterations are performed by linearizing the non-linear equations $[F(x)] = [0]$ and adjusting the values of x . This process can be visualized in the case of a single variable problem, which could be formed by subtracting the two equations used at the beginning of the Gauss- Siedel section, i.e.

$$f(x) = \text{eqn 1} - \text{eqn 2} \quad \{f(x) = 0 \text{ at the solution}\}$$

$f(x) = 0$ is the required solution.

The initial estimate is $x^0 \approx x + \Delta x$. This can be improved by applying trigonometry once the function has been differentiated.

An estimate for Δx is obtained from:

$$\Delta X^0 = f(X + \Delta X) / \frac{df(x + \Delta x)}{dx} \quad (3.7)$$

Then the estimate of x is improved by:

$$X^1 = X^0 - \Delta X^0 \quad (3.8)$$

Newton-Raphson (NR) method is an iterative solution algorithm for solving a set of simultaneous non-linear equations in an equal number of unknowns. At each iteration the non-linear problem is approximated by the linear matrix equation. The linearizing approximation can be visualized in the case of a single-variable problem. The NR algorithm will converge quadratic ally if the functions have continuous first derivatives in the neighborhood of the solution. The Jacobean matrix is non-singular, and the initial approximations of the state vectors are close to the Actual solutions. The method is sensitive to the behavior of the functions i.e. the more linear they are, the more rapidly and reliably the method converges. The NR method along with its companion techniques of sparsity and optimal ordering is successful in the AC load flow. The method works quite well for most of the system. The NR method, though Accurate and reliable for most of the system, is not very fast. Also, the method does not work well under heavy loading condition. However, there appears to be several drawbacks with this approach:

- The convergence characteristics are quadratic in nature.
- Speed advantage of the NR method in solving the AC part of the system particularly for large systems is not fully realized.
- Link calculation is time consuming and involves complex logic.
- The algorithm is relatively inflexible for adopting control Specifications.
- Convergence is of arbitrary nature and not fully Reliable.
- The method does not perform well under ill-conditioned situation.

The problems outlined above were mitigated by combining the AC load flow and DC link solution in an integrated NR solution process .Some modified version of AC-DC load

flow methods have been proposed [31]. This approach was claimed to be faster and more stable than the sequential one using the NR technique.

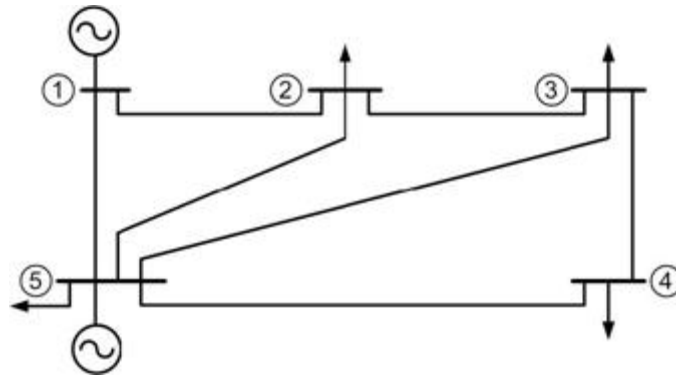


Figure 3.1 The simple power system used for load flow studies

Figure 3.1 shows the simple power system used for load flow studies. Let us assume that an n -bus power system contains a total n_p number of P-Q buses while the number of P-V (generator) buses be n_g such that $n = n_p + n_g + 1$. Bus-1 is assumed to be the slack bus. We shall further use the mismatch equations of ΔP_i and ΔQ_i respectively. The approach to Newton-Raphson load flow is similar to that of solving a system of nonlinear equations using the Newton-Raphson method. At each iteration we have to form a Jacobian matrix and solve for the corrections. For the load flow problem, this equation is of the form

$$[J] \begin{bmatrix} \Delta\delta_2 \\ \cdot \\ \cdot \\ \Delta\delta_n \\ \frac{\Delta|V_2|}{|V_2|} \\ \cdot \\ \cdot \\ \cdot \\ \frac{\Delta|V_{1+n_o}|}{|V_{1+n_o}|} \end{bmatrix} = \begin{bmatrix} \Delta P_2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta P_n \\ \Delta Q_2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta Q_{1+n_o} \end{bmatrix} \quad (3.9)$$

where the Jacobian matrix is divided into sub matrices as

$$J = \begin{bmatrix} J_{11}; J_{12} \\ J_{21}; J_{22} \end{bmatrix} \quad (3.10)$$

It can be seen that the size of the Jacobian matrix is $(n + n_p - 1) \times (n + n_p - 1)$. For example for the 5-bus problem of Figure. 3.1 matrix will be of the size (7×7) . The dimensions of the sub matrices are as follows:

$$J_{11}: (n - 1) \times (n - 1), J_{12}: (n - 1) \times n_p, J_{21}: n_p \times (n - 1) \text{ and } J_{22}: n_p \times n_p$$

The sub matrices are

$$J_{11} = \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} \cdots \frac{\partial P_2}{\partial \delta_n} \\ \vdots \\ \frac{\partial P_n}{\partial \delta_2} \cdots \frac{\partial P_n}{\partial \delta_n} \end{bmatrix} \quad (3.11)$$

$$J_{12} = \begin{bmatrix} |V_2| \frac{\partial P_2}{\partial |V_2|} \cdots |V_{1+n_o}| \frac{\partial P_2}{\partial |V_{1+n_o}|} \\ \vdots \\ |V_2| \frac{\partial P_n}{\partial |V_2|} \cdots |V_{1+n_o}| \frac{\partial P_n}{\partial |V_{1+n_o}|} \end{bmatrix} \quad (3.12)$$

$$J_{21} = \begin{bmatrix} \frac{\partial Q_2}{\partial \delta_2} \cdots \frac{\partial Q_2}{\partial \delta_n} \\ \vdots \\ \frac{\partial Q_{1+n_o}}{\partial \delta_2} \cdots \frac{\partial Q_{1+n_o}}{\partial \delta_n} \end{bmatrix} \quad (3.13)$$

$$J_{22} = \begin{bmatrix} |V_2| \frac{\partial Q_2}{\partial |V_2|} & \dots & |V_{1+n_o}| \frac{\partial Q_2}{\partial |V_{1+n_o}|} \\ \vdots & & \vdots \\ |V_2| \frac{\partial Q_{1+n_o}}{\partial |V_2|} & \dots & |V_{1+n_o}| \frac{\partial Q_{1+n_o}}{\partial |V_{1+n_o}|} \end{bmatrix} \quad (3.14)$$

3.2.4 LOAD FLOW ALGORITHM

The Newton-Raphson procedure is as follows:

Step-1: Read line data and bus data. The line data includes the line impedance and the transformer tap setting, the bus data include the type of bus load and generation level etc.

Step-2: Normalize the data to common base.

Step-3: Form the Y_{bus} using the line data.

Step-4: Set iter=0.

Step-5: Calculate the injected powers P_k and Q_k for all the buses except slack bus using eq. 3.4 and 3.5.

Step-6: Use the estimated V and δ to formulate the Jacobian matrix J .

Step-7: Solve eq. 3.9 to obtain the changes $\Delta\delta$ and $\left| \frac{\Delta V}{V} \right|$.

Step-8: Update the values of V and δ using eq. 3.15 and 3.16.

$$\delta = \delta + \Delta\delta \quad (3.15)$$

$$|V| = |V| + \left[1 + \frac{\Delta|V|}{|V|} \right] \quad (3.16)$$

Step-9: Check ΔP and ΔQ at all buses except slack bus. If ΔP and ΔQ within the tolerance then terminate the iterative process otherwise iter=iter+1 and go to step 5.

The flow chart of the above algorithm has been illustrated in Figure 3.2.

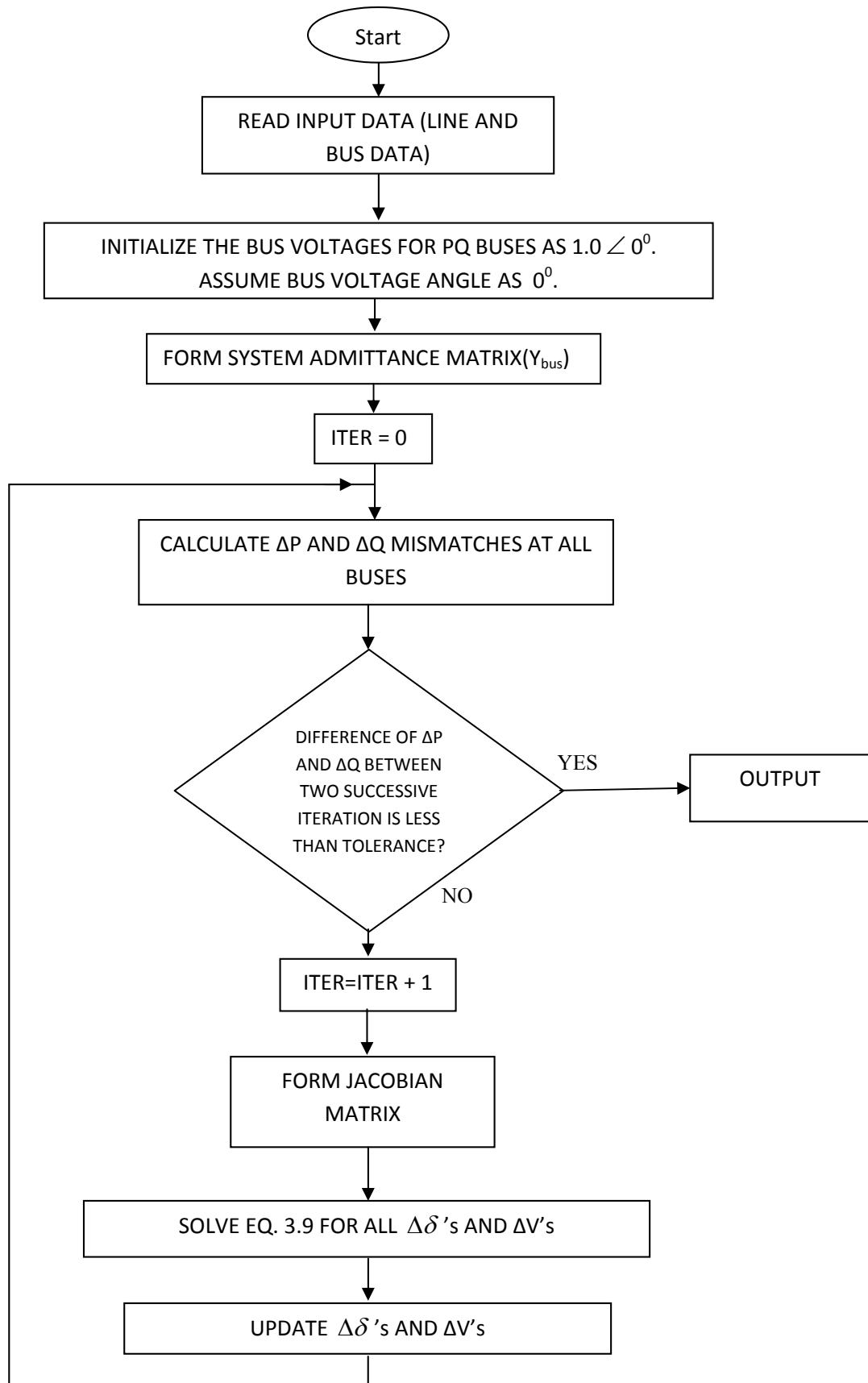


Figure 3.2 Flow chart for Newton-Raphson method

The basic information contained in the load-flow output is:

- i) All bus voltage magnitudes and phase angles w.r.t the slack bus.
- ii) All bus active and reactive power injections.
- iii) All line sending- and receiving-end complex power flows.
- iv) Individual line losses can be deduced by subtracting receiving-end complex power from sending-end complex power.

The most important information obtained from the load-flow is the voltage profile of the system. If $|V|$ varies greatly over the system, large reactive flows will result; this, in turn, will lead to increased real power losses and, in extreme cases, an increased likelihood of voltage collapse. When a particular bus has an unacceptably low voltage, the usual practice is to install capacitor banks in order to provide reactive compensation to the load. Load-flow studies are used to determine how much reactive compensation should be applied at a PQ bus, to bring its voltage up to an appropriate level.

3.3 LOAD FLOW IN HVDC

High Voltage Direct Current HVDC transmission links are in operation throughout the world. They are key elements in electrical power networks. Their representation is oversimplified or ignored in most power system studies. It is therefore necessary to adequately model the HVDC transmission links and integrate them in the load flow analysis of the complete AC/DC system. High Voltage Direct Current (HVDC) power distribution systems have been extensively used in modern transmission system. The major concern of the HVDC transmission is the load flow in the system.[32]

High Voltage Direct Current HVDC transmission constitutes a key application of the power electronics technology to electrical power networks. The economics of bulk power transmission by underground means is increasingly moving in favor of direct current. The HVDC links have the ability to exert instantaneous power control in neighboring AC systems. Great many research efforts have been directed towards realizing HVDC models for stability studies and power flows. However, HVDC models for OPF studies have received limited attention and are underdeveloped.

Power flow analysis is an essential component of system studies carried out for planning, designing and operation of power systems. It is basically simulation out of the

system in steady state and determines the operating point which is later used for initializing variables in transient and dynamic system simulation. The power flow or load flow analysis of AC system has been thoroughly investigated in terms of numerical algorithms for obtaining the solution to the nonlinear algebraic equations.

Although there is a little work reported on analytical aspects such as the existence and number of solutions, the convergence characteristic of differential algorithm etc. there are several production grade computer programs that can handle large systems with thousands of buses and lines. For most of the cases, the use of flat start results in convergence to a solution that is in most of the cases the unique and stable operation point. For implementing load flow analysis in HVDC we need to do first the modeling of DC links and then use it in the load flow analysis.

3.3.1 INTEGRATION OF THE DC LINK EQUATIONS WITH AC LOAD FLOW

The sequential approach for integration of the HVDC link equations in an AC load flow program has been followed. In this approach, the AC and DC link equations are solved separately and thus the integration into standard load-flow program is carried out without significant modifications of the AC load flow algorithm. For the AC system iterations, each converter is simply modeled as a complex power load at the AC terminal bus-bar. The DC link equations are solved using the latest updated value of the AC bus bar voltage.

As opposed to the sequential approach, the unified approach, which gives full recognition to the inter-dependence (through weak) between the AC and DC system equations, involves solving the AC and DC system equations simultaneously. However, because of the weak interdependence of the AC-DC equations, the sequential approach is only marginally inferior to the unified approach and hence gives good results except in the case of a very weak AC system. Advantages of the sequential approach include easy integration with existing AC load flow program, faster execution speed and less storage.

Another reason for using the sequential approach is that it is very much compatible with the fast decoupled algorithm. As the real and reactive power equations have been decoupled, so the AC system and the DC link equations have been decoupled.[33,34]

3.3.2 MODELLING THE DC LINK IN A POWER SYSTEM

Figure 3.3 shows the schematic diagram of the basic model of the DC link interconnecting bus bars (r) and (i).

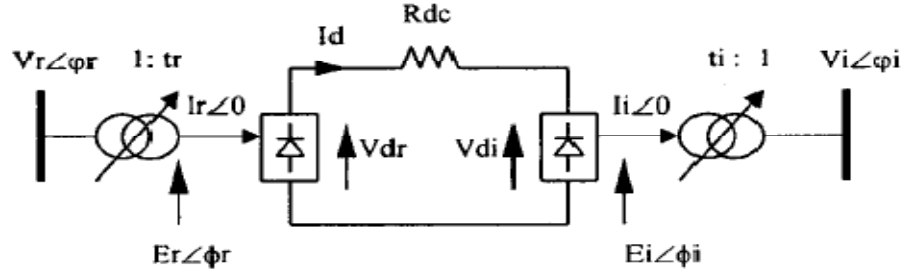


Figure 3.3 Schematic diagram of DC link

The following variables are involved in the representation, and need to be discussed:

1. V -converter terminal bus bar nodal voltage with phase angle referred to converter reference.
2. $E\angle\Phi$ - alternating voltage at the converter transformer secondary.
3. $I\angle 0$ -alternating current at the converter transformer secondary.
4. γ, β -firing & extinction angle respectively.
5. t -transformer tap ratio.
6. V_d, I_d -direct voltage and current at the link.

In the results of the load flow, we would usually be interested in the AC bus bar voltages and the converter end DC voltages. Thus E may be treated as an intermediate variable and eliminated from the equations. Similarly, we are more interested in the DC link current than the converter transformer secondary current. Hence $I\angle 0$ may also be eliminated from the equations. In the sequential approach, since we model the converters as constant loads on the AC. system, Φ need not be used as a variable. The value of V is available as the latest updated AC voltage at the converter bus bar. We are now left with $V_{dr}, V_{di}, t_r, t_i, \gamma, \beta$ and I_d . We have four equations relating, these seven variables. They are:

$$V_{dr} = V_{di} + R_{dc} I_d \quad (3.17)$$

$$P_{dr} = V_{dr} I_d \text{ or } P_{di} = V_{di} I_d \quad (3.18)$$

$$V_{dr} = K1 * t_r * V_r * \cos \gamma - 3 / \Pi * I_d * X_r \quad (3.19)$$

$$V_{di} = K1 * t_i * V_i * \cos \beta - 3 / \Pi * I_d * X_i \quad (3.20)$$

Either the rectifier end power (P_{dr}) or the inverter end power (P_{di}) is usually specified as data. The inverter bus voltage and the minimum values of γ and β are also specified as data. Now all the DC link variables are obtained and the modeling of the link is complete.[17,35]

3.4 ALGORITHM OF AC-DC LOADFLOW

Equations for modeling the DC link have been derived and have been integrated with the AC load flow program. A flowchart of the same is given in Figure 3.4.

If P_{dr} is specified, then knowing I_d , V_{dr} is calculated from equation (3.18). Then equation (3.17) is used to obtain the value of V_{di} . If, on the other hand, P_{di} is specified, then equation (3.17) and (3.18) are solved simultaneously to get the values of V_{di} and V_{dr} by knowing the value of I_d . To keep the reactive power consumption of the converters minimum, it is necessary to keep the values of γ and β as close to their minimum value as possible. Hence we set $\gamma = \gamma_{\min}$ and $\beta = \beta_{\min}$. Using the latest updated value of V_i and V_r in equations (3.19) and (3.20) and solving for the DC variables, we now calculate the real and reactive power at each converter. The complex power expression at converter 'c' is.

$$S(c) = V_d(c)I_d + jV_d(c)I_d \tan \phi(c) \quad (3.21)$$

Where,

$$\tan \phi(c) = \text{sgn}(c)2X + \sin 2\theta(k) - \sin(\theta(c) + X) / \cos 2\theta(c) - \cos 2(\theta(c) + X) \quad (3.22)$$

And

$$X = \cos^{-1}[2V_d(c) / V_o(c) - \cos \theta(c)] - \theta(c) \quad (3.23)$$

Where

$$V_o(c) = \frac{3\sqrt{2}}{\pi} V(c)$$

where, $V(c)$ is the alternating phase-phase voltage at the converter terminals.

In the above expression,

If converter (c) is the rectifier, then $\theta(c) = \gamma$ and $\text{sgn}(c) = 1$.

If converter (c) is the inverter, then $\theta(c) = \beta$ and $\text{sgn}(c) = -1$.

One iteration of the AC load flow is carried out assuming constant complex power loads at the converter bus bars. This gives new values of V_r and V_i and these are used in equations (3.19) and (3.20) to get new values of t_r and t_i and hence new values of complex power. The above procedure is repeated until the AC load flow converges.[36-39]

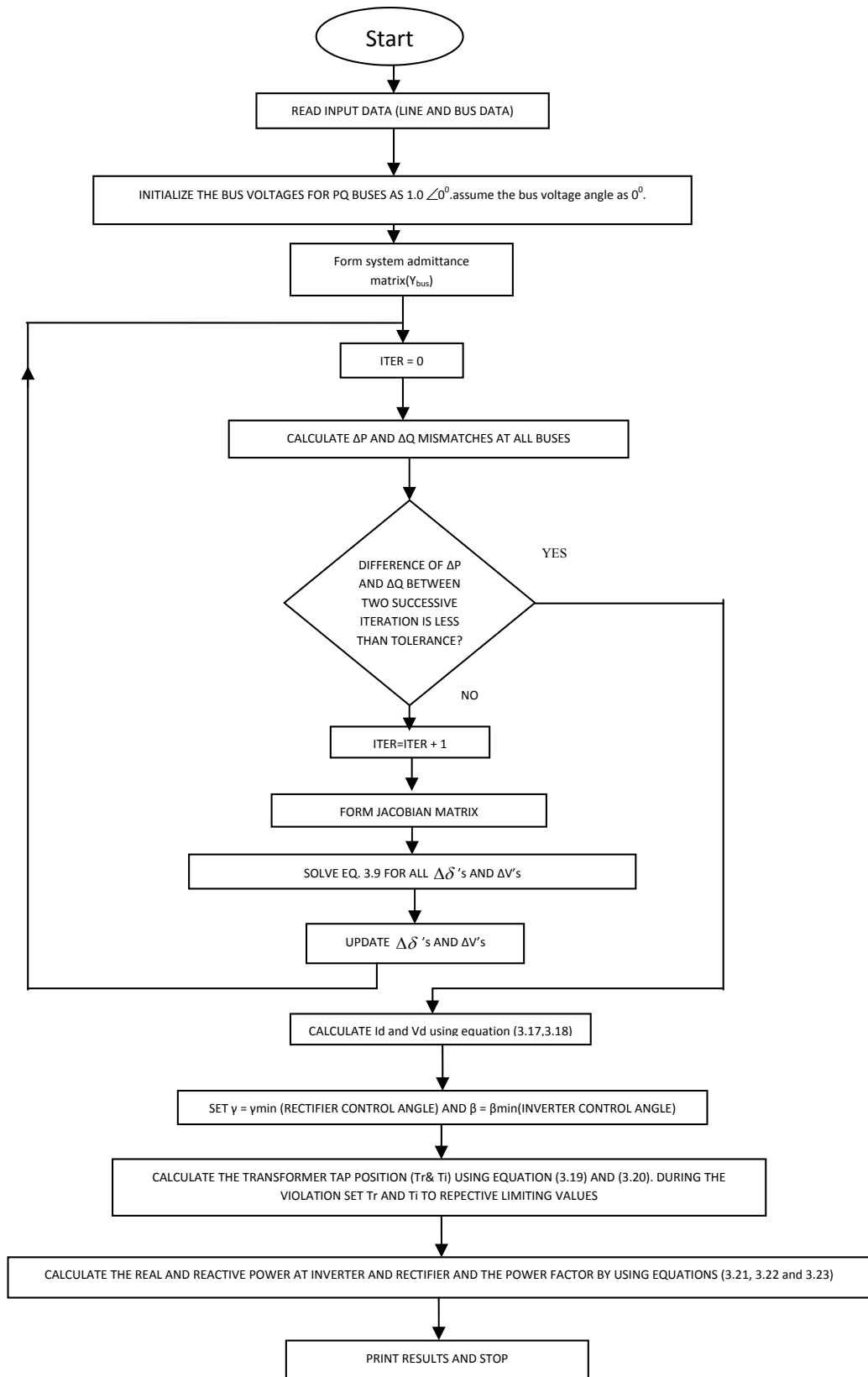


Figure 3.4 Flow chart of AC-DC load flow algorithm

CHAPTER-4

RESULTS AND DISCUSSION

4.1 GENERAL

The main focus is here the integration of HVDC link with an AC power system. Variables of the direct current link which have been chosen for simulation are the converter terminal DC voltages, converter transformer tap ratios, firing angle of the rectifier and current in the HVDC link. Algorithm that has been presented to solve the power load flow with HVDC link, has been tested on the various IEEE test systems. Design of a HVDC link converter substation is very dependent upon the characteristic of the DC link such as the commutation reactance. In modern converter station, the range of the commutation reactance is from 0.1 to 0.15 per unit.

The study has been carried out for the following system standards:

- 9-bus system
- 11-bus system
- 14-bus system

The following conventions were used for all test bus systems, Base MVA=100; bus type: 1-Slack bus, 2-PV bus, 3-PQ bus.

4.2 9-Bus SYSTEM

The test system is a standard 9-bus system. The bus data and line data for 9-bus system has been given in table 4.1 and 4.2 respectively. The line connecting bus 4 and 5 of the system is replaced by a DC link, DC link data have been given in table 4.3. The diagram for the system is given in Figure 4.1 [17].

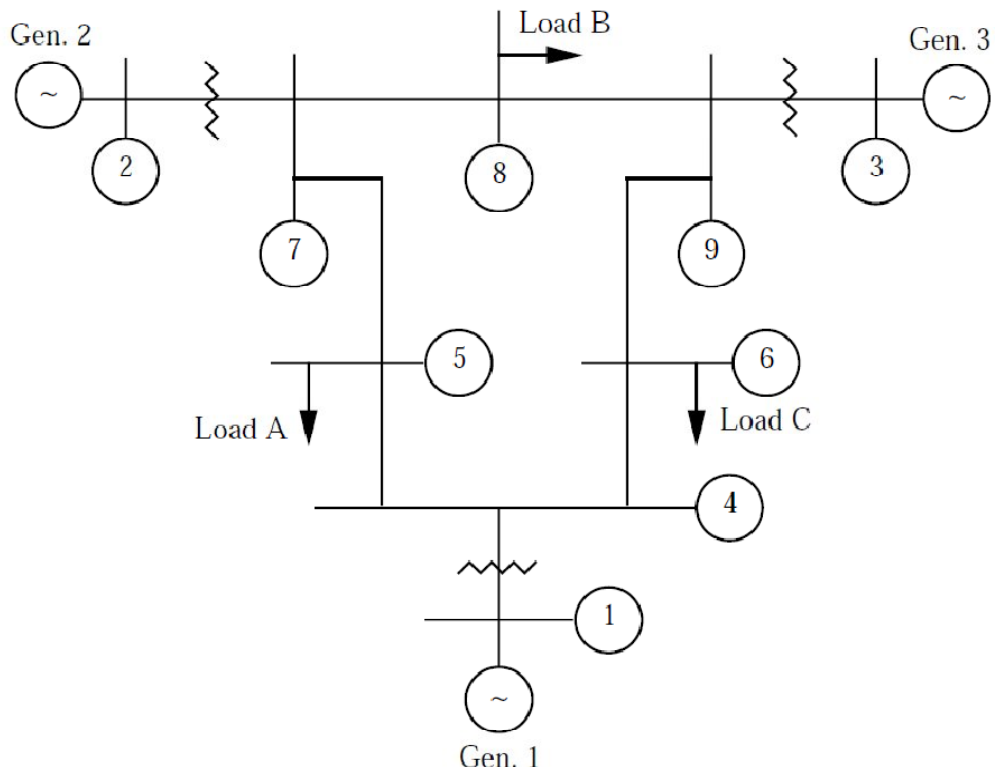


Figure 4.1 Representation of 9-bus system [DC link 5 (rectifier) 4 (inverter)]

**Table 4.1
Bus Data for 9-bus system**

Bus	Bus Type	Voltage Specified	Gen. MW	Gen. MVAR	Load MW	Load MVAR	Qmin	Qmax
1	1	1	0	0	0	0	-300	300
2	2	1	163	0	0	0	-300	300
3	2	1	85	0	0	0	-300	300
4	3	-	0	0	0	0	0	0
5	3	-	0	0	90	30	0	0
6	3	-	0	0	0	0	0	0
7	3	-	0	0	100	35	0	0
8	3	-	0	0	0	0	0	0
9	3	-	0	0	125	50	0	0

Table 4.2
Line Data for 9-bus system

Start Bus	End bus	R(pu)	X(pu)	1/2B(pu)	Tap Set Value
1	4	0	0.0576	0.00	1
4	5	0.017	0.092	0.079	1
5	6	0.039	0.17	0.179	1
3	6	0	0.0586	0	1
6	7	0.0119	0.1008	0.1045	1
7	8	0.0085	0.072	0.0745	1
8	2	0	0.0625	0	1
8	9	0.032	0.161	0.153	0.978
9	4	0.01	0.085	0.088	0.969

Table 4.3
DC link characteristic for 9-bus system

	Rectifier	Inverter
Bus Number	5	4
Commutation Reactance	0.126	0.0725
Minimum Control Angle	7	10
Number Of Tap Position	27	19
Resistance Of DC Line	0.00334	
DC Power Flow Setting	0.587	
Inverter End DC voltage	1.284	

Load flow has been carried out for this 9-bus system and the results are presented in table 4.4 and 4.5 for the AC system and for the AC system with HVDC link respectively. variation in the bus voltage and bus voltage angles are shown in figure. 4.2. The DC link parameters for this load flow are summarized in table 4.6.

Table 4.4
AC Load flow results for 9-bus system

Bus No	Voltage	Angle	Real Power	Reactive Power
1	1.0000	0	0.7195	0.2407
2	1.0000	9.6687	1.63	0.1446
3	1.0000	4.7711	0.8500	-0.0365
4	0.9870	-2.4066	0	0
5	0.9755	-4.0173	-0.9000	-0.3000
6	1.0034	1.9256	0	0
7	0.9856	0.6215	-1.0000	-0.3500
8	0.9962	3.7991	0	0
9	0.9576	-4.3499	-1.2500	-0.5000

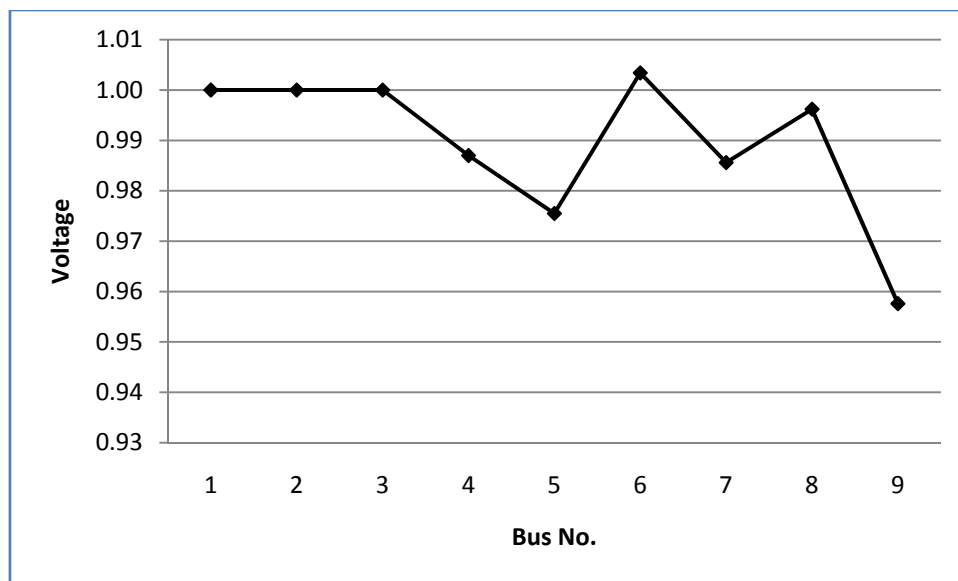


Figure 4.2 Graphical representation of the various AC bus voltages for 9-bus system

Table 4.5
DC Link (5-4) results for 9-bus system

	Rectifier	Inverter
DC voltage	1.2855	1.2840
Transformer tap position	0.9707	0.9565
Control angles	1.5542	1.5546
Real power flow	0.586	0.585
Reactive power flow	0.0206	0.5952
Power factor	0.935	0.978
Current in DC link	0.4562	

From the above study it is observed that the DC voltage at the rectifier end and the inverter end are obtained as 1.2855 and 1.2840 respectively. This suggests the rectified DC voltage is greater than the inverted DC voltage. The transformer tap settings for rectifier end and inverter end are obtained as 0.9707 and 0.9565 respectively. This suggests the transformer tap settings for rectifier terminal is greater than the inverter terminal. This is in accordance with the AC system results. Which is maintaining higher voltage at rectifier end i.e. bus 5 and compared to inverter end bus i.e bus 4. The reactive power demand is much lower than the real power exchange by the converter terminals and therefore they are maintaining high power factor.

4.3 14-BUS SYSTEM

Figure 4.2 [16] gives the Single Line Diagram (SLD) of the 14 bus system. The data given is in the IEEE common data format. For the 14 bus system the base MVA is 100 MVA and the Q limits are to be enforced. Q limits specify the limits to which reactive power can be generated or absorbed by a bus where voltage is being controlled. Such buses, where voltage is being controlled are known as PV buses. These limits are normally specified in the generator data of a system.

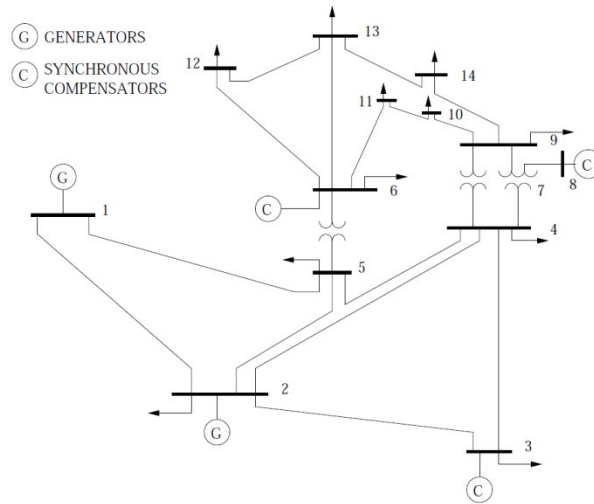


Figure 4.3 Representation of 14-bus system [DC link 5 (rectifier) 4 (inverter)], DC link 1 (rectifier) 2 (inverter)]

If the Q limits are violated in a bus, the voltage is no more controlled at that bus. If the Q limits are not enforced, it will be considered that the generator has abundant reactive power supply, and voltage has to be controlled, no matter what amount of reactive power is needed. Buses 1 and 2 have generators. Buses 1, 2, 3, 6 and 8 are PV (Active power P and voltage magnitude V are held constant) buses. The rest of the buses are PQ (Active power P and reactive power Q are held constant) buses.

The bus data and line data for 14-bus system has been given in table 4.6 and 4.7 respectively. DC links data have been given in table 4.8 and 4.9 respectively.

**Table 4.6
Bus Data for 14-bus system**

Bus	Bus Type	Voltage Specified	Gen. MW	Gen. MVAR	Load MW	Load MVAR	Qmin	Qmax
1	1	1.0600	0	0	0	0	0	0
2	2	1.045	40	4204	21.7	12.7	-40	50
3	2	1.010	0	23.4	94.2	19.0	0	40
4	3	1	0	0	47.8	-3.9	0	0
5	3	1	0	0	7.6	1.6	0	0

Bus	Bus Type	Voltage Specified	Gen. MW	Gen. MVAR	Load MW	Load MVAR	Qmin	Qmax
6	2	1.070	0	12.2	11.2	7.5	-6	24
7	3	1	0	0	0	0	0	0
8	2	1.090	0	17.4	0	0	-6	24
9	3	1	0	0	29.5	16.6	0	0
10	3	1.0	0	0	9.0	5.8	0	0
11	3	1.0	0	0	3.5	1.8	0	0
12	3	1.0	0	0	6.1	1.6	0	0
13	3	1.0	0	0	13.5	5.8	0	0
14	3	1.0	0	0	14.9	5.0	0	0

Table 4.7
Line Data for 14-bus system

Start Bus	End bus	R(pu)	X(pu)	1/2B(pu)	Tap Set Value
1	2	0.01938	0.05917	0.0264	1
1	5	0.05403	0.22304	0.0246	1
2	3	0.04699	0.19797	0.0219	1
2	4	0.05811	0.17632	0.0170	1
2	5	0.05695	0.17388	0.0173	1
3	4	0.06701	0.17103	0.0064	1
4	5	0.01335	0.04211	0	1
4	7	0	0.20912	0	0.978
4	9	0	0.55618	0	0.969
5	6	0	0.25202	0	0.932
6	11	0.09498	0.19890	0	1
6	12	0.12291	0.25581	0	1
6	13	0.06615	0.13027	0	1
7	8	0	0.17615	0	1
7	9	0	0.11001	0	1

Start Bus	End bus	R(pu)	X(pu)	1/2B(pu)	Tap Set Value
9	10	0.03181	0.08450	0	1
9	14	0.12711	0.27038	0	1
10	11	0.08205	0.19207	0	1
12	13	0.22092	0.19988	0	1
13	14	0.17093	0.34802	0	1

Table 4.8
First DC link characteristic for 14-bus system

	Rectifier	Inverter
Bus Number	5	4
Commutation Reactance	0.126	0.0725
Minimum Control Angle	7	10
Number Of Tap Position	27	19
Resistance Of DC Line	0.00334	
DC Power Flow Setting	0.587	
Inverter End DC voltage	1.284	

Table 4.9
Second DC link characteristic for 14-bus system

	Rectifier	Inverter
Bus Number	1	2
Commutation Reactance	0.1512	0.0873
Minimum Control Angle	8	10
Number Of Tap Position	25	20
Resistance Of DC Line	0.00334	
DC Power Flow Setting	0.587	
Inverter End DC voltage	1.284	

Previous system discussed was for only single link in 9-bus system. But with a little modification algorithm for multiple DC link have been developed. Multiple DC links in a system can also be treated very easily. For example, in the case of two DC links, we shall have eight equations (for each link) for the DC variables each of which is to be solved as explained earlier and both the links will be modeled as complex power loads for the AC iterations. The line connecting bus bars 1 and 2 of the 14 bus system was replaced by a DC link characteristics of which are given in Table 4.9. The load flow program was run to obtain the results given in Table 4.10, 4.11, 4.12. This illustrates the case of multiple DC links as well as the case of a DC link between two generator buses. Graphical variation of the output AC bus voltages with respect to the bus nodes have been shown in Figure.

Table 4.10
AC Load flow results for 14-bus system

Bus No.	Voltage	Angle	Real Power	Reactive Power
1	1.0600	0	2.3253	-0.2251
2	1.0450	-4.9565	0.1830	0.1806
3	1.0100	-12.6328	-0.9420	0.0105
4	1.0261	-10.3659	-0.4780	0.0390
5	1.0326	-8.9467	-0.0760	-0.0160
6	1.0700	-14.8794	-0.1120	0.4162
7	1.0448	-13.4503	0	0
8	1.0900	-13.4503	0	0.2796
9	1.0276	-15.0699	-0.2950	-0.1660
10	1.0275	-15.3181	-0.0900	-0.0580
11	1.0449	-15.2134	-0.0350	-0.0180
12	1.0530	-15.7197	-0.0610	-0.0160
13	1.0462	-15.7383	-0.1350	-0.0580
14	1.0174	-16.3940	-0.1490	-0.0500

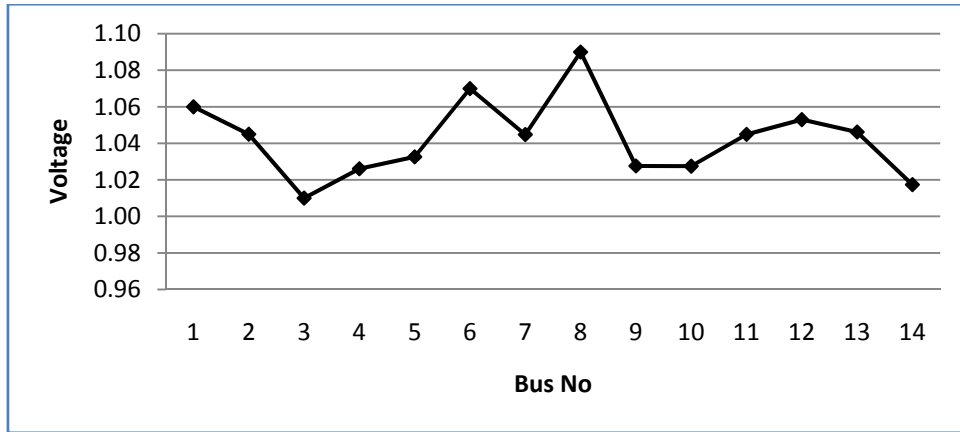


Figure 4.4 Graphical representation of the various AC bus voltages for 14-bus system

Table 4.11

First DC link (5-4) results for 14-bus system

	Rectifier	Inverter
DC voltage	1.2855	1.2840
Transformer tap position	1.0275	0.9944
Control angles	1.5522	1.5533
Real power flow	0.586	0.5857
Reactive power flow	0.0205	0.5953
Power factor	0.9552	0.9436
Current in DC link	0.4562	

Table 4.12

Second DC link (1-2) results for 14-bus system

	Rectifier	Inverter
DC voltage	1.2415	1.2370
Transformer tap position	1.1221	1.0341
Control angles	1.5487	1.5518
Real power flow	1.5858	1.5801
Reactive power flow	0.0547	0.0538
Power factor	0.9807	0.9320
Current in DC link	1.2774	

From the above study it is observed that the DC voltage at the rectifier end and the inverter end are obtained as 1.2855 and 1.2840 respectively for the first DC link and 1.2415 and 1.2370 respectively. This suggests the rectified DC voltage is greater than the inverted DC voltage for the both DC links included in the 14-bus system. The transformer tap settings for rectifier end and inverter end are obtained as 1.0275 and 0.9944 respectively for the first DC link whereas 1.1221 and 1.0341 respectively. This suggests the transformer tap settings for rectifier terminal is greater than the inverter terminal for both of the DC links. This is in accordance with the AC system results. The reactive power demand is much lower than the real power exchange by the converter terminals and therefore they are maintaining high power factor.

4.4 11-BUS SYSTEM

The algorithm is tested on another 11-busbars power system as shown in Figure 4.3[17]. The line connecting bus bar 5 and 6 are replacing by a DC link with the characteristic as given in Table 4.15.

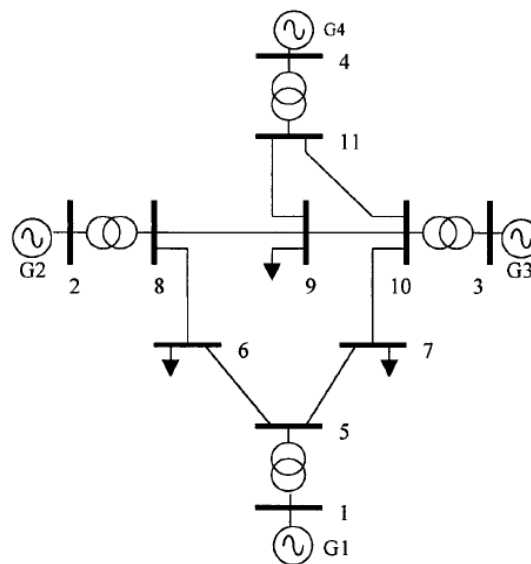


Figure 4.5 Representation of 11-bus system [DC link 5 (rectifier) 6 (inverter)]

The bus data and line data for 11-bus system has been given in table 4.13 and 4.14 respectively. DC link data have been given in table 4.15.

Table 4.13
Bus Data for 11-bus system

Bus	Bus Type	Voltage Specified	Gen. MW	Gen. MVAR	Load MW	Load MVAR	Qmin	Qmax
1	1	1.024	0	0	0	0	0	0
2	2	1	0	0	0	0	-1	1
3	3	1	0	0	12.8	6.2	0	0
4	2	1	0	0	0	0	-1	1
5	3	1	0	0	16.5	8	0	0
6	3	1	0	0	9	6.8	0	0
7	2	1	0	0	0	0	-1	1
8	2	1	0	0	0	0	-1	1
9	3	1	0	0	2.6	0.9	0	0
10	2	1.0	0	0	0	0	-1	1
11	3	1.0	0	0	15.8	5.7	0	0

Table 4.14
Line Data for 11-bus system

Start Bus	End bus	R(pu)	X(pu)	1/2B(pu)	Tap Set Value
1	5	0	0.0576	0	1
5	6	0.0100	0.0850	0.0880	1
5	7	0.0170	0.0920	0.0790	1
6	8	0.0320	0.1610	0.1530	1
7	10	0.0390	0.1700	0.1790	1
2	8	0	0.0635	0	1
8	9	0.0085	0.0720	0.0745	1
9	10	0.0119	0.1008	0.0251	0.978
3	10	0.0000	0.0586	0	0.969
9	11	0.0119	0.1008	0.0251	0.932
4	11	0	0.0586	0.0251	1
10	11	0.12291	0.25581	0	1

Table 4.15
DC link characteristic for 11-bus system

	Rectifier	Inverter
Bus Number	5	6
Commutation Reactance	0.1126	0.07275
Minimum Control Angle	8	10
Number Of Tap Position	20	15
Resistance Of DC Line	0.00334	
DC Power Flow Setting	0.5857	
Inverter End DC voltage	1.284	

The result of AC simulation is given in Table 4.16 and the DC link result is given in Table 4.17. Graphical variation of the output AC bus voltages have been shown in Figure. As shown in Figure bus voltages have all the variations around 1 pu value. Graphical variation for the DC bus voltages have been shown in Figure for the respective bus nodes for the DC link (5-6).

Table 4.16
AC Load flow results for 11-bus system.

Bus No.	Voltage	Angle	Real Power	Reactive Power
1	1.0240	0	0.5714	0.0657
2	1.0000	-3.7943	0	0
3	0.9963	-4.9145	-0.1280	-0.0620
4	1.0000	-4.7639	0	-0.0166
5	1.0208	-1.8044	-0.1650	-0.0800

Bus No.	Voltage	Angle	Real Power	Reactive Power
6	1.0235	-2.8570	-0.0900	-0.0680
7	1.0000	-2.5829	0	-0.4882
8	1.0000	-3.7943	0	-0.4448
9	1.0060	-4.3655	-0.0260	-0.0090
10	1.0000	-4.4831	0	-0.2729
11	1.0010	-4.7639	-0.1580	-0.0570

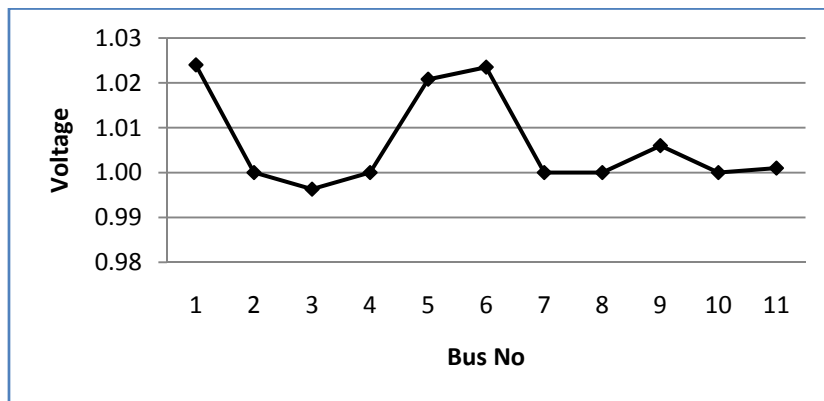


Figure 4.6 Graphical representation of the various AC bus voltages for 11-bus system.

Table 4.17

DC link (5-6) results for 11-bus system

	Rectifier	Inverter
DC voltage	1.2855	1.2840
Transformer tap position	0.9691	0.914
Control angles	1.5561	1.5542
Real power flow	0.5864	0.5857
Reactive power flow	0.0208	0.5953
Power factor	0.934	0.985
Current in DC link	0.456	

From the above study it is observed that the DC voltage at the rectifier end and the inverter end are obtained as 1.2855 and 1.2840 respectively. This suggests the rectified DC voltage is greater than the inverted DC voltage. The transformer tap settings for rectifier end and inverter end are obtained as 0.9691 and 0.914 respectively. This suggests the transformer tap settings for rectifier terminal is greater than the inverter terminal. This is in accordance with the AC system results. Which is maintaining higher voltage at rectifier end i.e. bus 5 and compared to inverter end bus i.e bus 6. The reactive power demand is much lower than the real power exchange by the converter terminals and therefore they are maintaining high power factor.

CHAPTER-5

CONCLUSION AND FUTURE SCOPE

5.1 CONCLUSIONS

An approach for carrying out the power flow analysis of an integrated AC-DC power system has been presented. A DC link model presented in simplified form and has been integrated with standard AC load flow program. The simulation on a 9-Bus, 14-Bus, and 11-Bus system has been illustrated. The following conclusions are drawn:

- The formulation is such that a minimum amount of modifications are necessary in basic AC load flow program, so advantage of the algorithm in terms of time and memory are retained.
- The algorithm is capable to handle multiple HVDC links.
- The DC voltage at rectifier end is more than the DC voltage at inverter terminal.
- Transformer tap positions at the rectifier terminal are high compared to transformer tap positions at the respective inverter end of the DC link.
- Two converters of the respective DC links are operating nearly at same power factor.

5.2 SCOPE FOR FUTURE WORK

New energy sources including renewable energy sources are being developed rapidly, which can be linked easily to DC systems than to AC systems. So HVDC link is going to play a very crucial role in modern power system. The power flow analysis is vital for any power system. Having studied the power flow analysis of system with HVDC links, The followings can be taken up for further study and analysis:

- Stability studies of AC systems can be done further which includes HVDC links.
- Economic scheduling of generation in AC systems joined by an HVDC link need to be investigated further.

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