Certain Analytical Aspects of AC-DC Power System with FACTs controllers in Smart Grid

Chintalapudi V Suresh

Professor, Department of Electrical and Electronics Engineering, Vasireddy Venkatadri Institute of Technology, Nambur, Guntur, Andhra Pradesh, India. venkatasuresh3@vvit.net

B. Sreenivasa Raju

Associate Professor, Department of Electrical and Electronics Engineering, Vasireddy Venkatadri Institute of Technology, Nambur, Guntur, Andhra Pradesh, India. eee.raju@gmail.com

ABSTRACT

This abstract presents a comprehensive overview of the AC-DC load flow analysis method, a critical component of power system studies for modern electrical grids. The integration of renewable energy sources and the growing use of high-voltage direct current (HVDC) transmission have necessitated the development of advanced load flow techniques that can accurately model and optimize the power flow in hybrid AC-DC systems. The AC-DC load flow analysis is a numerical algorithm used to calculate steady-state power flow across mixed AC and HVDC networks. Unlike traditional AC load flow, this method considers additional parameters, such as HVDC converter characteristics, control strategies, and interconnection constraints. By effectively incorporating these factors, the algorithm enables better representation of power flow dynamics and facilitates the integration of renewable energy sources and large-scale HVDC transmission. The detailed representation of AC and HVDC components, such as generators, transformers, transmission lines, and converters, is crucial to capturing the system's behavior accurately. Special attention is given to HVDC converters, which can significantly impact power flow due to their ability to control power transfer and voltage. The abstract concludes by highlighting the importance of AC-DC load flow analysis in ensuring the reliable and secure operation of contemporary power systems. As renewable energy sources and HVDC transmission continue to gain prominence, understanding and implementing accurate load flow methods are essential for achieving a sustainable and resilient energy future.

Keywords— AC-DC load flow, power system analysis, HVDC transmission, renewable energy integration, power flow optimization.

# INTRODUCTION

In recent years, the power industry has witnessed significant transformations, driven by the increasing adoption of renewable energy sources and the need for long-distance electricity transmission. This shift has led to the integration of high-voltage direct current (HVDC) transmission into traditional alternating current (AC) power systems, giving rise to hybrid AC-DC power grids. However, the efficient and reliable operation of such hybrid systems necessitates a deeper understanding of power flow interactions between AC and DC components. The load flow analysis has long been a fundamental technique used to analyze power systems, ensuring that the demand and supply of electricity are balanced while maintaining stable voltage levels. Historically focused on AC networks, traditional load flow methods may prove inadequate when it comes to addressing the unique characteristics and complexities introduced by HVDC transmission. The AC-DC load flow analysis emerges as a crucial tool to address these challenges and cater to the evolving power system landscape. Unlike conventional AC load flow, the AC-DC load flow analysis extends its scope to encompass both AC and HVDC components, considering the characteristics of HVDC converters, power control strategies, commutation processes, and transmission constraints.

In this, we discuss the key components of the AC-DC load flow analysis, including: AC and HVDC Network Modeling: The detailed representation of AC and HVDC components, such as generators, transformers, transmission lines, and converters, is crucial to capturing the system's behavior accurately. Special attention is given to HVDC converters, which can significantly impact power flow due to their ability to control power transfer and voltage. Hybrid AC-DC Power Flow Equations: The load flow equations are modified to include HVDC power control equations and additional constraints imposed by the HVDC transmission system. These modified equations provide a comprehensive understanding of the interactions between the AC and DC components, enabling accurate power flow calculations. Control Strategies and Stability Considerations: HVDC systems employ various control strategies to regulate power flow and maintain system stability. The abstract explores the impact of these control mechanisms on overall power flow and system performance, including stability analysis. Optimization Techniques: With the increasing complexity of modern power systems, optimization techniques play a vital role in enhancing system efficiency and reliability. The abstract discusses various optimization methods, such as Newton-Raphson and Gauss-Seidel algorithms, used to solve the AC-DC load flow problem efficiently.

The main objectives of the AC-DC load flow analysis are twofold: accurate representation and efficient optimization. Firstly, it aims to accurately model the behavior of HVDC systems within the context of a broader power network, ensuring that the interactions between AC and DC components are well understood and appropriately accounted for. Secondly, the analysis seeks to optimize power flow paths and maximize the utilization of the transmission infrastructure, minimizing losses and enhancing overall energy efficiency. Renewable energy integration plays a significant role in the evolution of modern power systems. The intermittent nature of renewable resources necessitates dynamic power flow management to ensure smooth integration and utilization. HVDC transmission proves beneficial in facilitating the transfer of renewable energy from resource-rich regions to areas with high electricity demand, but effective load flow analysis is essential to optimize these transfers and maximize the use of clean energy sources. Furthermore, with the expansion of power grids and the interconnectedness of regional networks, system stability and reliability become paramount concerns. The AC-DC load flow analysis plays a critical role in evaluating the impact of HVDC converter controls and power modulation on overall system stability, ensuring secure operation under various operating conditions.

The integration of renewable energy sources and high-voltage direct current (HVDC) transmission has significantly impacted power system analysis and management. As modern power grids evolve into hybrid AC-DC systems, researchers have been investigating various aspects of AC-DC load flow analysis to address the challenges arising from this integration [1]. This comprehensive review explores the integration of HVDC transmission into AC load flow analysis. The authors examine various methodologies and algorithms proposed to accurately model HVDC converters, control strategies, and commutation processes. The paper discusses the impact of HVDC on power flow patterns, voltage profiles, and system stability in hybrid AC-DC networks [2]. This systematic review focuses on load flow optimization techniques in hybrid AC-DC power systems. The authors survey various optimization algorithms, such as Newton-Raphson, Gauss-Seidel, and evolutionary algorithms. The paper emphasizes the importance of load flow optimization in minimizing transmission losses, enhancing energy efficiency, and achieving optimal power flow in integrated AC-DC grids [3]. This research investigates the impact of renewable energy sources, such as solar and wind power, on AC-DC load flow analysis. The authors address the challenges posed by the intermittent nature of renewables and their integration into hybrid power systems. The study discusses the use of energy storage systems and advanced control strategies to ensure grid stability and efficient power flow [4]. This paper reviews the role of Flexible AC Transmission System (FACTS) devices, such as Static Var Compensators (SVC) and Thyristor-Controlled Series Compensators (TCSC), in AC-DC load flow analysis. The authors examine different control strategies employed by FACTS devices to regulate voltage, improve power quality, and enhance system stability. The research highlights the importance of coordinated control between FACTS devices and HVDC converters for optimal performance in hybrid AC-DC networks [5]. This research paper provides a comprehensive review of the challenges and recent advances in AC-DC load flow analysis of power systems. It discusses the complexities arising from the integration of HVDC transmission, FACTS devices, and renewable energy sources. The study presents innovative solutions and state-of-the-art techniques to improve load flow analysis accuracy and efficiency in hybrid AC-DC grids [6]. Focusing on harmonic analysis, this study explores the impact of SVC and TCSC integration in AC-DC load flow analysis. The authors investigate harmonic generation and mitigation challenges introduced by these FACTS devices. The paper presents harmonic modeling techniques to assess power quality and equipment performance, emphasizing the importance of harmonic studies for reliable and efficient operation in hybrid AC-DC power systems [7]. This study explores the coordinated control of HVDC and FACTS devices in AC-DC load flow analysis for optimal power flow management. The authors propose control strategies to enhance power system stability, voltage regulation, and minimize transmission losses. The paper highlights the benefits of synergistic control between HVDC converters and FACTS devices for improving the overall performance of hybrid AC-DC grids [8]. This research investigates real-time AC-DC load flow analysis considering large-scale renewable energy integration. The study addresses the challenges of intermittent renewables and their impact on power system stability. It presents real-time simulation techniques to assess grid performance, contingency analysis, and dynamic response in hybrid AC-DC power systems with significant renewable energy penetration [9]. AC-DC load flow analysis remains crucial for understanding and optimizing hybrid power systems. Efforts are continuously being made to improve modeling techniques, convergence algorithms, and data availability to enhance the reliability and applicability of AC-DC load flow studies. In this paper, a methodology and mathematical modeling to model AC-DC load flow problem along with necessary graphical and numerical results are presented.

# MATHEMATICAL MODELING OF AC-DC LOAD FLOW PROBLEM

A concise mathematical modeling of AC-DC load flow with equations:

1. AC Network Equations:
   * Nodal Voltage Equations (AC):

For each AC bus i, the nodal voltage is represented as:

ViAC​=∣ViAC​∣∠δiAC​

Active Power (P) and Reactive Power (Q) Equations (AC):

* + The active and reactive power at AC bus i are given by:

PiAC​=∣ViAC​∣∑j=1n​∣VjAC​∣(Gij​cos(δiAC​−δjAC​)+Bij​sin(δiAC​−δjAC​))

QiAC​=∣ViAC​∣∑j=1n​∣VjAC​∣(Gij​sin(δiAC​−δjAC​)−Bij​cos(δiAC​−δjAC​))

where: |V\_i^{AC}|: Voltage magnitude at bus i in the AC network. δiAC​: Phase angle at bus i in the AC network. n: Total number of buses in the AC network. G\_{ij}: Conductance between buses i and j in the AC network. B\_{ij}: Susceptance between buses i and j in the AC network.

1. DC Network Equations:
   * Nodal Voltage Equations (DC):

For each DC bus i, the nodal voltage is represented as:

ViDC​=ViDC​

* + Active Power (P) Equations (DC):

The active power at DC bus i is given by:

PiDC​=∑j=1m​ViDC​VjDC​Gij​

* + DC Power Flow Equations:

The power flow between two DC buses i and j is given by:

PijDC​=(ViDC​−VjDC​)Gij​

where: ViDC​: Voltage magnitude at bus i in the DC network. m: Total number of buses in the DC network. G\_{ij}: Conductance between buses i and j in the DC network.

The AC and DC load flow equations are typically solved iteratively to find the steady-state operating conditions of the hybrid AC-DC power system. This process involves initializing the voltage magnitudes and phase angles, and then iteratively updating these values until the system reaches a converged solution. Various numerical methods, such as the Gauss-Seidel or Newton-Raphson method, can be used for solving these equations efficiently.

## **Evaluation of Derivatives**

The diagonal and off-diagonal elements for each of the sub-matrices in the Jacobian matrix are given below:

A sub matrix

B sub matrix

C sub matrix

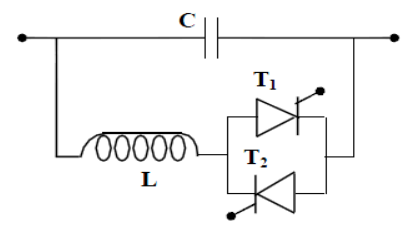
D sub matrix

# MODELING OF SERIES FACTS CONTROLLERS

Series FACTS (Flexible AC Transmission Systems) controllers are power electronics-based devices used to control and enhance the transmission of electrical power in AC (alternating current) systems. They are installed in series with the transmission line and can regulate the line impedance and voltage, leading to an improvement in power transfer capability and system stability. These devices play a crucial role in modern power systems by providing dynamic control and flexibility, especially in dealing with transmission congestion and stability issues. It is important to note that while series FACTS controllers offer significant benefits, their deployment and operation require careful consideration and coordination to avoid any potential issues related to system protection, stability, and harmonics. Thus, comprehensive system studies and simulations are conducted before implementing series FACTS devices in the power grid.

## **Operating principle of TCSC**

The Thyristor-Controlled Series Capacitor (TCSC) is a type of series FACTS (Flexible AC Transmission System) controller used in power systems to enhance transmission line control and stability. Its operating principle involves the control of the line reactance using thyristor switches in a series capacitor configuration shown in Fig.1.



**Fig.1 Model of TCSC**

To analyze the effect of this device, TCSC should be incorporated in a given system. For this, power injection model of this device is described as follows:

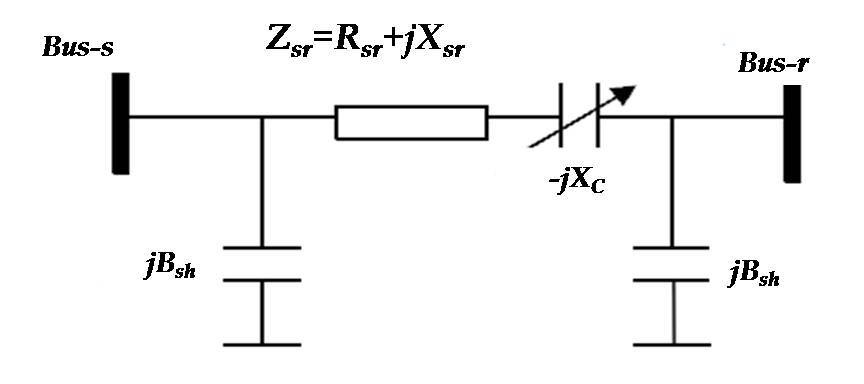
In a straightforward transmission system, depicted with π-equivalent parameters, there is a connection between bus-s and bus-r. The power flow of real and reactive power from bus-s to bus-r can be expressed as follows:

Where

The real and reactive power flows from bus-r to bus-s is

## **Power Injection Model of TCSC**

Figure 2 depicts a transmission line model with a Thyristor-Controlled Series Capacitor (TCSC) connected between bus-s and bus-r. Under steady-state conditions, the TCSC is represented as a static reactance. In the power flow equations, the controllable reactance is directly employed as the control variable.



**Fig.3.2 Transmission line with TCSC**

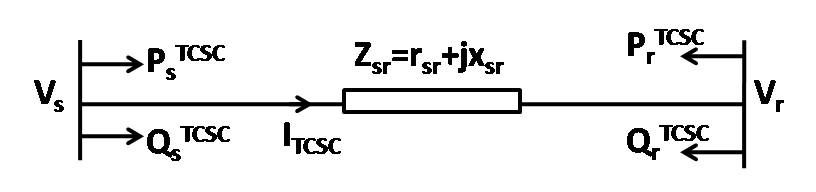
By introducing the TCSC in series with the line, the line data will be adjusted. The new line reactance is provided as follows:

Hence, the new line admittance between buses "s" and "r" can be obtained through the following derivation:

;

The revised active and reactive power flows between bus-s and bus-r, as well as between bus-r and bus-s, for a line incorporating series impedance and series reactance are as follows:

The power loss in the transmission line equipped with TCSC can be expressed as follows:



**Fig.3 Power injection model of TCSC**

Due to the presence of TCSC, the changes in line flow can be visualized as an equivalent line without TCSC, accompanied by power injections at both the sending and receiving ends of the line, as depicted in Fig.3. The active and reactive power injections at bus-s and bus-r can be mathematically expressed as follows:

Where

,

The TCSC device has been modeled using a power injection approach, incorporating the TCSC control variable. Consequently, it is feasible to compute the complex power injected at bus-s and bus-r, respectively.

,

Subsequently, the new power flow equations can be formulated using the following relationship:

Where, new mismatch vectors are

and These are the conventional specified real and reactive powers, and These are the power injections associated with TCSC devices. and The power injections linked to TCSC devices are calculated using the power flow equations. Subsequently, the modified Jacobian matrix, resulting from the power injections of TCSC, can be obtained as follows:

;

;

H, M, N and L are the classic sub-Jacobian matrices.

# MODELING OF SHUNT FACTS CONTROLLERS

As per the IEEE definition, a Static Var Compensator (SVC) is a shunt-connected device responsible for generating or absorbing reactive power. Its output can be precisely adjusted to exchange capacitive or inductive current, effectively regulating specific parameters within the electrical power system, often focusing on maintaining bus voltage.

SVCs find extensive application in power systems to elevate voltage levels, thereby enhancing overall system stability. By offering reactive power support, SVCs play a vital role in ensuring voltage remains within acceptable limits and mitigating voltage fluctuations, thereby contributing to a dependable and consistent power supply.

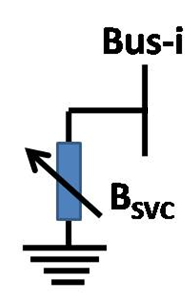
## **Modeling of SVC**

In practical scenarios, the SVC can be seen as an adjustable reactance with either firing-angle limits or reactance limits. To derive the SVC nonlinear power equations, the equivalent circuit shown in Fig.4 is utilized. As per Fig.4, the current drawn by the SVC is computed using the following formula:

The reactive power drawn by the SVC, which is also the reactive power injected at bus-i, can be determined as follows:

The SVC is designed as a set of three-phase static capacitors and/or inductors. During heavy loading conditions, when positive reactive power (VAr) is required, capacitor banks are employed, while inductor banks are used for negative VAr requirements. In this thesis, the SVC is represented as an ideal reactive power injection at bus-i, as illustrated in Fig.4.

Top of Form



**Fig.4 Power injection model of SVC**

# POWER SYSTEM PERFORMANCE PARAMETERS

This section provides an explanation of various electrical parameters within a power system and their influence on the overall system parameters. It delves into how changes in these parameters can impact the performance and behavior of the power system.

## **Generation fuel cost**

The primary goal of a power generation system is to fulfill the demand while minimizing fuel costs. The total fuel cost function can be mathematically expressed as follows:

The total generation fuel cost, represented by 'FC,' is obtained by summing up the individual fuel cost functions for each generating unit 'Ci(PGi).' In this equation, 'PGi' represents the power generated by the ith unit, and 'NG' denotes the total number of generating units.

The objective function is formulated as a quadratic fuel cost function. The quadratic fuel cost of a thermal generating unit can be represented using a second-order polynomial function in the following manner:

where, ai, bi, and ci are the fuel-cost coefficients of the ith unit,

## **Emission objective**

The emission of gases in the boiler is characterized by the aggregation of various gases emitted, such as NO2, SO2, thermal emission, among others. The quantity of emitted gases is dependent on the generator output and is represented as follows,

where is the emission of the generator

The emission curve is represented in quadratic function as

(ton/h)

Where are the emission coefficients of the generator

## **Total Power Losses**

The objective function utilized to compute the total power loss (TPL) involves the power flow through a line, which can be determined from the power flow solution. The power loss can be expressed as follows:

Where is the real power loss in line

## **Transmission Line Voltage Regulation**

Voltage regulation of a transmission line is defined as the percentage ratio of the difference between the sending and receiving end voltages to the receiving end voltage, considering the conditions of no load and full load.

The voltage regulation (%VR) can be expressed mathematically as:

Here, Vs represents the sending end voltage per phase, and VR is the receiving end voltage per phase.

The sending end voltage (Vs) is calculated using the following formula:

Where XL is the reactance per phase, R is the resistance per phase, θR is the receiving end power factor.

## **Transmission Efficiency**

Transmission efficiency is defined as the percentage ratio of the receiving end power (PR) to the sending end power (PS) in a power transmission system. It represents the efficiency with which power is transferred from the sending end to the receiving end of the transmission line. The transmission efficiency is expressed as a percentage value.

## **Corona loss**

Whenever corona is formed in a power system, energy loss is unavoidable, and it dissipates through various forms, including light, heat, sound, and chemical reactions. When the voltage exceeds the disruptive threshold, the power loss due to corona can be mathematically expressed as follows:

F=frequency in Hz

# RESULTS AND ANALYSIS

The efficiency of the developed methodology is assessed using the IEEE-14 bus test system [Ref]. This system comprises fourteen buses, twenty-one transmission lines, with five generators located at buses 1, 2, 3, 6, and 8, one shunt compensator at bus-9, and three tap-changing transformers installed in lines 8 (between buses 4 and 7), 9 (between buses 4 and 9), and 10 (between buses 5 and 6). The total active and reactive power loads are 246.05 MW and 69.825 MVAr, respectively. To formulate the AC-DC network, the 13th transmission line, which connects buses 7 and 9, is considered as the DC link. In this line, the rectifier is connected at bus-7, and the inverter is connected at bus-9.

E:\B.Tech 17-18\IEEE-14 BUS WITH DC LINK.tif

**Single line diagram of IEEE-14 bus system with DC link**

The entire analysis is performed for the following modules:

Module-1: Identifying the effectiveness of AC-DC network over conventional AC network.

Module-2: Analyzing the effect of converter parameters such as rectifier delay angle (α) and inverter extinction angle (β) on system parameters. For this, these angles are varied from 0 deg to 360 deg in steps of 20 deg.

Module-3: Analyzing the effect of AC-DC load flow on various power system parameters.

Module-4: Analyzing the effect of FACTs controllers such as SVC and TCSC on various power system parameters when compared to without device.

## **Module-1**

In this module, both NR load flow problem is solved for the AC network and AC-DC networks. To identify the effect of DC link on system parameters, the rectifier delay angle (α) and inverter extinction angle (β) are assumed to be 60 deg and 220 deg respectively. The obtained load flow results for the voltage magnitude and voltage angles are tabulated in Table.1. From this, it is identified that, the voltage magnitude at bus-7 is enhanced and bus-9 is decreased. This is due to operation of α < 180 deg and β > 180 deg. The variation of voltage magnitudes and voltage angles are shown in Figs.5 and 6.

### **Table.1 Voltages with AC-DC NR load flow method for IEEE-14 bus system**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Bus No** | **VM, p.u.** | | **VA, deg** | |
| **AC NR** | **AC-DC NR** | **AC NR** | **AC-DC NR** |
| 1 | 1.06 | 1.06 | 0 | 0 |
| 2 | 1.045 | 1.045 | -2.312 | -2.243 |
| 3 | 1.011 | 1.012 | -6.012 | -5.866 |
| 4 | 1.024 | 1.024 | -5.945 | -5.844 |
| 5 | 1.026 | 1.026 | -4.98 | -4.93 |
| 6 | 1.07 | 1.07 | -8.048 | -8.244 |
| 7 | 1.064 | 1.065 | -7.781 | -7.264 |
| 8 | 1.09 | 1.09 | -6.911 | -6.395 |
| 9 | 1.057 | 1.053 | -9.299 | -9.756 |
| 10 | 1.052 | 1.049 | -9.35 | -9.76 |
| 11 | 1.058 | 1.056 | -8.828 | -9.131 |
| 12 | 1.056 | 1.056 | -8.898 | -9.115 |
| 13 | 1.051 | 1.051 | -9.016 | -9.249 |
| 14 | 1.038 | 1.035 | -10.124 | -10.487 |

**E:\B.Tech 17-18\MODULE-1\VMPLOT.tif**

**Fig.5 Variation of voltage magnitude with AC-DC NR load flow method for IEEE-14 bus system**

**E:\B.Tech 17-18\MODULE-1\VAPLOT.tif**

**Fig.6 Variation of voltage angle with AC-DC NR load flow method for IEEE-14 bus system**

Similarly, the power flow results are tabulated in Table.2. From this result, it is identified that, power flow through DC link is decreased from 27.95 MVA to 23.909 MVA. The variation of power flow is shown in Fig.7.

### **Table.2 Power flows with AC-DC NR load flow method for IEEE-14 bus system**

|  |  |  |
| --- | --- | --- |
| **Line No** | **Power flow, MVA** | |
| **AC NR** | **AC-DC NR** |
| 1 | 76.618 | 74.547 |
| 2 | 44.28 | 43.896 |
| 3 | 37.687 | 36.943 |
| 4 | 38.723 | 38.407 |
| 5 | 29.421 | 29.636 |
| 6 | 8.871 | 8.638 |
| 7 | 40.226 | 38.066 |
| 8 | 18.875 | 15.72 |
| 9 | 11.759 | 13.71 |
| 10 | 28.866 | 30.64 |
| 11 | 9.261 | 10.513 |
| 12 | 7.934 | 8.101 |
| 13 | 18.945 | 19.602 |
| 14 | 18.577 | 18.19 |
| 15 | 27.95 | 23.909 |
| 16 | 5.845 | 5.068 |
| 17 | 8.755 | 7.993 |
| 18 | 5.536 | 6.732 |
| 19 | 1.842 | 2.003 |
| 20 | 6.633 | 7.429 |

**E:\B.Tech 17-18\MODULE-1\SFLOWPLOT.tif**

**Fig.7 Variation of power flow with AC-DC NR load flow method for IEEE-14 bus system**

Furthermore, the results for active and reactive power losses, number of iterations, and time taken for convergence are tabulated in Table 3. The analysis reveals that the total active power losses decrease with the inclusion of the DC link in the AC network. Similarly, the total number of iterations required for convergence is reduced. However, due to the increased computational complexity, the time taken for convergence is extended.

### **Table.3 Power losses and performance parameters with AC-DC NR load flow method for IEEE-14 bus system**

|  |  |  |
| --- | --- | --- |
| **Parameters** | **AC NR** | **AC-DC NR** |
| Active power losses, MW | 4.635 | 4.563 |
| Reactive power losses, MVAr | -8.665 | -8.441 |
| Number of Iterations | 5 | 4 |
| Time, Sec | 0.053 | 0.097 |

## **Module-2**

Furthermore, to examine the impact of DC link converters on system performance, the analysis is conducted by varying the rectifier delay angle (α) and inverter extinction angle (β). These angles are systematically changed from 0 degrees to 360 degrees in increments of 20 degrees.

At each angle variation, the minimum and maximum voltage magnitudes at buses, along with their corresponding α and β values, are recorded and presented in Table 4. The analysis reveals that the generator connected at bus-3 is no longer operating as a PV bus due to the rectifier operation at bus-5. Additionally, the maximum voltage difference is observed at bus-3, while the minimum difference is observed at bus-12. A graphical representation of the voltage differences at various buses is illustrated in Fig. 8.

### **Table.4 Variation of voltage magnitudes with AC-DC NR load flow method for IEEE-14 bus system**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Bus No** | **Vmin**  **(p.u.)** | **α**  **(deg)** | **β**  **(deg)** | **Vmax**  **(p.u.)** | **α**  **(deg)** | **β**  **(deg)** | **Vdiff**  **(p.u.)** |
| 1 | 1.06 | 0 | 0 | 1.06 | 0 | 0 | 0 |
| 2 | 1.045 | 0 | 0 | 1.045 | 0 | 0 | 0 |
| 3 | 1.01 | 0 | 80 | 1.012 | 60 | 240 | -0.0028 |
| 4 | 1.024 | 60 | 80 | 1.025 | 0 | 240 | -0.0007 |
| 5 | 1.026 | 60 | 80 | 1.026 | 0 | 240 | -0.0004 |
| 6 | 1.07 | 0 | 0 | 1.07 | 0 | 0 | 0 |
| 7 | 1.065 | 60 | 80 | 1.065 | 0 | 240 | -0.0003 |
| 8 | 1.09 | 0 | 0 | 1.09 | 0 | 0 | 0 |
| 9 | 1.053 | 0 | 180 | 1.054 | 60 | 20 | -0.0003 |
| 10 | 1.049 | 0 | 180 | 1.049 | 60 | 20 | -0.0002 |
| 11 | 1.056 | 0 | 180 | 1.056 | 60 | 20 | -0.0001 |
| 12 | 1.056 | 60 | 80 | 1.056 | 0 | 240 | -2E-05 |
| 13 | 1.051 | 0 | 180 | 1.051 | 60 | 20 | -4E-05 |
| 14 | 1.035 | 0 | 180 | 1.035 | 60 | 20 | -0.0002 |

**Vdiff=Vmax-Vmin**

**E:\B.Tech 17-18\MODULE-2\VOLTAGEDIFF.tif**

**Fig.8 Variation of voltage difference with AC-DC NR load flow method for IEEE-14 bus system**

Similarly, for each step of angles variation, the minimum and maximum power flow in transmission lines along with respective α and β values are tabulated in Table.5. From this table, it is observed that, the first transmission line connected to slack has major variation of power flow. As the generation from slack bus is increased to divert the power to the loads. The variation of power flow difference in lines is shown in Fig.9.

### **Table.5 Variation of power flow with AC-DC NR load flow method for IEEE-14 bus system**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Line No** | **Smin**  **(p.u.)** | **α**  **(deg)** | **β**  **(deg)** | **Smax**  **(p.u.)** | **α**  **(deg)** | **β**  **(deg)** | **Sdiff**  **(p.u.)** |
| 1 | 74.537 | 60 | 0 | 78.592 | 0 | 60 | -4.055 |
| 2 | 43.895 | 60 | 0 | 44.967 | 0 | 60 | -1.072 |
| 3 | 36.879 | 0 | 220 | 38.34 | 60 | 60 | -1.461 |
| 4 | 38.262 | 0 | 220 | 38.77 | 60 | 60 | -0.508 |
| 5 | 29.443 | 0 | 220 | 29.822 | 60 | 60 | -0.38 |
| 6 | 8.308 | 60 | 240 | 9.444 | 0 | 80 | -1.136 |
| 7 | 38.06 | 60 | 0 | 39.018 | 0 | 160 | -0.958 |
| 8 | 15.679 | 0 | 140 | 15.775 | 60 | 80 | -0.096 |
| 9 | 13.679 | 0 | 280 | 13.711 | 60 | 120 | -0.032 |
| 10 | 30.605 | 60 | 300 | 30.692 | 0 | 140 | -0.088 |
| 11 | 10.511 | 60 | 120 | 10.556 | 0 | 280 | -0.045 |
| 12 | 8.1 | 60 | 340 | 8.107 | 0 | 180 | -0.007 |
| 13 | 19.6 | 60 | 120 | 19.626 | 0 | 180 | -0.025 |
| 14 | 18.149 | 0 | 240 | 18.295 | 60 | 80 | -0.146 |
| 15 | 23.875 | 0 | 280 | 23.909 | 60 | 220 | -0.034 |
| 16 | 5.027 | 0 | 80 | 5.083 | 60 | 240 | -0.056 |
| 17 | 7.963 | 0 | 180 | 7.997 | 60 | 340 | -0.034 |
| 18 | 6.732 | 60 | 120 | 6.772 | 0 | 280 | -0.04 |
| 19 | 2.003 | 60 | 340 | 2.01 | 0 | 180 | -0.007 |
| 20 | 7.429 | 60 | 120 | 7.457 | 0 | 280 | -0.028 |

**Sdiff=Smax-Smin**

**E:\B.Tech 17-18\MODULE-2\SFLOWDIFF.tif**

**Fig.9 Variation of power flow difference with AC-DC NR load flow method for IEEE-14 bus system**

At last, minimum and maximum power losses along with respective α and β values are tabulated in Table.6. From this, it is observed that, there is a power loss difference of 0.222 MW with DC link.

### **Table.6 Variation of power loss with AC-DC NR load flow method for IEEE-14 bus system**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Plossmin**  **(MW)** | **α**  **(deg)** | **β**  **(deg)** | **Plossmax**  **(MW)** | **α**  **(deg)** | **β**  **(deg)** | **Plossdiff**  **(MW)** |
| P loss,  MW | 4.562806 | 60 | 220 | 4.78495 | 0 | 60 | 0.222144 |

## **Module-3**

To extend the benefit of AC-DC transmission for power system performance enhancement, certain power system parameters are considered and the corresponding results are tabulated in Table.7. Due to DC link, the sending and receiving end voltage magnitudes are increased, this in turn decreases the line current, power flows, total generation, generation cost, emission of flue gases and total power losses. Also, voltage regulation is decreased which increases the total transmission efficiency. It is also observed that, in AC-DC system, corona losses are decreased by 62.6053 kW when compared to AC system.

### **Table.7 Power system parameters with AC-DC NR load flow method for IEEE-14 bus system**

|  |  |  |  |
| --- | --- | --- | --- |
| **S. No** | **Parameter** | **AC NR method** | **AC-DC NR method** |
| 1 | Sending end voltage magnitude  (VS), p.u. | 1.063954 | 1.064737 |
| 2 | Receiving end voltage magnitude  (Vr), p.u. | 1.057153 | 1.059124 |
| 3 | Line current (Iline), Amps | 0.2433-j0.0990 | 0.2089-j0.0855 |
| 4 | Active power flow (7-9), MW | 27.07624 | 23.21865 |
| 5 | Reactive power flow (7-9), MVAr | 6.935814 | 5.705615 |
| 6 | Apparent power flow (7-9), MVA | 27.95046 | 23.90941 |
| 7 | Total generation, MW | 250.68528 | 250.61281 |
| 8 | Generation cost, $/hr | 2175.0675 | 2150.9896 |
| 9 | Emission, ton/hr | 10.639068 | 10.366526 |
| 10 | Total power losses, MW | 4.6352826 | 4.5628056 |
| 11 | Voltage regulation of line (%) | 47.5161 | 38.9745 |
| 12 | Transmission efficiency | 82.5830 | 82.8166 |
| 13 | Corona loss (kW/km) | 94.0826 | 31.4773 |

## **Module-4**

To evaluate the influence of FACTS controllers on system performance, two types of controllers, the Static VAr Compensator (SVC) as a shunt controller and the Thyristor-Controlled Series Compensator (TCSC) as a series controller, are taken into account.

To determine the optimal placement of the SVC, a bus with low voltage is identified after conducting the AC-DC load flow analysis (as shown in Table 1). Bus-14 is selected as the ideal location for the SVC installation, as it lacks sufficient nearby generator support. The SVC is sized at 50 MVAr.

Similarly, for the series controller (TCSC), a line with a high power flow margin, which indicates the difference between rated capacity and actual power flow, is chosen. In this case, line-6, connecting buses 3 and 4, is considered the most suitable location. The TCSC device's size is set at 80% of the transmission line reactance (0.8 \* Xline = 0.034206).

Upon conducting the AC-DC load flow analysis with SVC and TCSC individually, the results for power system parameters are tabulated in Table 8. The analysis clearly demonstrates that the series and shunt compensations influence the power system parameters according to the nature of their compensation.

Top of Form

### **Table.8 Power system parameters with SVC and TCSC for IEEE-14 bus system**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **S. No** | **Parameter** | **Without**  **device** | **With SVC** | **With TCSC** |
| 1 | Sending end voltage magnitude  (VS), p.u. | 1.064737 | 1.085152 | 1.064074 |
| 2 | Receiving end voltage magnitude  (Vr), p.u. | 1.059124 | 1.106271 | 1.052851 |
| 3 | Line current (Iline), Amps | 0.2089-  j0.0855 | 0.2313+  j0.0662 | 0.2085-  j0.0855 |
| 4 | Active power flow (7-9), MW | 23.21865 | 23.94129 | 23.17092 |
| 5 | Reactive power flow (7-9), MVAr | 5.705615 | -10.411 | 6.190107 |
| 6 | Apparent power flow (7-9), MVA | 23.90941 | 26.10697 | 23.98351 |
| 7 | Total generation, MW | 250.61281 | 251.79422 | 250.66277 |
| 8 | Generation cost, $/hr | 2150.9896 | 2177.4353 | 2155.329 |
| 9 | Emission, ton/hr | 10.366526 | 11.705576 | 10.413689 |
| 10 | Total power losses, MW | 4.5628056 | 5.7442168 | 4.6127721 |
| 11 | Voltage regulation of line (%) | 38.9745 | 45.9981 | 34.4679 |
| 12 | Transmission efficiency | 82.8166 | 87.2366 | 82.8055 |
| 13 | Corona loss (kW/km) | 31.4773 | 34.3264 | 31.1075 |

# CONCLUSIONS

After conducting a thorough literature review, it has been observed that power transfer through a DC link leads to improved system performance compared to conventional AC transmission. To validate this observation, a novel load flow approach for AC-DC systems has been developed. This approach incorporates the sending end rectifier and receiving end inverters in a manner that accounts for the effects of DC transmission in the AC load flow problem. The project presents a comprehensive mathematical formulation to solve the AC-DC load flow problem, along with the integration of the load flow procedure. The analysis indicates that the use of DC transmission enhances overall system performance, resulting in improved voltage profiles and reduced total losses. Furthermore, the study investigates the impact of rectifier delay angle and inverter extinction angles on power system parameters such as voltage magnitude, voltage angle, power flow, and total system losses. The analysis reveals significant variations in the voltage profile near the buses where the DC link is connected. Moreover, the project explores the influence of FACTs controllers on AC-DC system performance in terms of power losses, generation cost, emission levels, voltage regulation, transmission efficiency, and corona losses. The findings demonstrate a notable enhancement in system performance when FACTs controllers are employed in the AC-DC power system compared to the AC power system.

##### REFERENCES

1. W. Xi-Fan, S. Yonghua and I. Malcolm, Modern Power Systems Analysis, lSBN 978- 0-387-72852-0, 2009.
2. G. John and S. William, Power System Analysis, Mcgraw-Hill: lSBN 0-07-061293-5, 1994.
3. Glenn W. Stagg, Ahmed H. El-Abiad, Computer Methods in Power Systems, Mcgraw-Hill, 1968.
4. H. E. Brown, G. K. Carter, H. H. Happ and C. E. Person, "Power Flow. Solution By Impedance Matrix Method," IEEE Trans. Power Apparatus and System, April 1963.
5. Robert G. Andretich, Homxier E. Brown, Harvey H. Happ and Conrad E. Person, "The Piecewise Solution of The Impedance Matrix Load Flow," IEEE Transactions on Power Apparatus And Systems, October 1968,Vol. PAS-87, No. 10, pp.1877-1882.
6. William F. Tinney and Clifford E. Hart, "Power Flow Solution By Newton's Method," IEEE Transactions On Power Apparatus And Systems, Nov. 1967.
7. Stott. B. and Alasc. O., "Fast Decoupled Load Flow," IEEE Transactions On Power Apparatus And Systems, PAS-93, pp.859-869, 1974.
8. J. W. Allen and F. W. Bruce, power Generation, Operation, And Control, Wiley, ISBN:978-0471586999, 1996.
9. P. S. R. Murty, Operation And Control In Power Systems, Taylor And Francis: ISBN: 9780415665650, 2011.
10. T. Nguyen, "Neural Network Load-Flow," IEEE Proceedings of Generation Transmission Distribution, Vol. 142, No. 1, Jan. 1995, pp. 51-58.