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An Intelligent Frequency Control Scheme for Inverting Station in High Voltage Direct Current Transmission System

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ABSTRACT

Power system stability is crucial for the reliable and efficient operation of electrical grids. One of the key factors affecting power system stability is the frequency of the alternating current (AC) system while connected with High Voltage Direct Current (HVDC) transmission system. Changes in load demand can lead to frequency deviations, which can have detrimental effects on the stability and performance of the power system. Frequency should therefore be controlled within predefined limits in order to prevent unexpected disturbances that may cause problems to connected loads or even cause the entire system to fail. A broad simulation model of the HVDC transmission system is developed using MATLAB software to evaluate the effectiveness of the proposed controllers such as Adaptive Neuro-Fuzzy Inference System (ANFIS), Artificial Neural Network (ANN), and optimization of Proportional-Integral-Derivative (PID) controller using Particle Swarm Optimization (PSO) based control strategy for addressing the frequency instability problems. To assess how well the ANFIS, ANN, and PID-PSO controller controls frequency in HVDC transmission system, several situations were simulated, including load disturbances and changes in operational circumstances. The result reveals that the ANN controller performs more accurate results in HVDC transmission system than the other proposed control and, displaying its capacity to successfully reduce frequency deviations and maintained a controlled frequency 50 Hz. Adopted method suggested the easy integration of HVDC with AC grid and enhances the system power quality and stability.

1 | Introduction

Electricity is generated using vast variety of sources, for instance, fossil fuels, nuclear energy or renewable sources such as solar and wind [1]. The power is transmitted to substations, where they are stepped down from high voltages to lower voltages, and transmitted to residences, commercial buildings and factories. The power system gives us steady flow of electricity by balancing demand and maintaining stability. In today's world, it is absolutely a necessity to run our houses, businesses, transportation and technological breakthroughs without furnace oil [2]. HVDC transmission is a technology involving the transfer of electric power at high voltages but with direct current (DC), in contrast to the alternation current used in conventional transmission. Due to lower line losses and capacity for underground or underwater power transmission, this technology is preferred for long distance

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power transmission [3]. HVDC systems contain rectifier stations that transform AC power into DC, and inverter stations that transform DC power into AC for the purpose of distribution. Since the transmission of electricity through HVDC systems has to be carefully monitored and controlled in order to ensure steady and dependable operation [4]. Frequency regulation is an indispensable aspect of the power system stability because it guarantees that power generation and consumption are balanced. Control of AC power frequency is a critical element of the system. Unlike AC systems, frequency regulation difficulties for HVDC transmission systems are unique. In AC systems, frequency control is usually exercised by adjusting generation and load in the network of the system. Finally, because the HVDC link has no impact on the frequency of the AC system as electricity is transmitted as such in HVDC system. However, additional measures are needed in HVDC transmission systems to guarantee frequency stability [5]. For these reasons, in this paper, we only focus on applying ANFIS, ANN, and PID-PSO optimize controller to realize the frequency stabilization of HVDC transmission systems.

ANFIS is a combination of fuzzy logic, which can reason similar to human being, and neural network, which has the ability to adapt. Because of this ability to simulate the complicated and nonlinear power system, for ANFIS has found extensive use in many areas of power systems [6]. For the implementation of ANFIS based frequency regulation in HVDC transmission systems, a control system must be designed that uses ANFIS models for prediction of system behavior and adjustment of generation and load. ANFIS models are trained with historical data and expert knowledge to capture system's dynamic response under different operating conditions. By using these models, one can predict the system's future behavior and decide on the right control measures to guarantee frequency stability [7]. The knowledge of the relationship between system parameters and optimal control operations is utilized by ANN for frequency control in HVDC transmission systems. With real time data of frequency deviations and load changes, the ANN makes accurate control signals. To maintain a stable frequency, ANN operates non deterministically, but based on historical data adjusting its response. Therefore by following this approach the stability of power system is improved and adjustment to inverter operation can be performed timely such that power will be transmitted reliably in HVDC [8]. The parameters of PID controller for frequency control in HVDC transmission systems are optimized using PSO based algorithm. The parametric values of Kp, Ki, and Kd (PID controller) are iteratively optimized by PSO using particle movement in a search space. By changing the operating conditions of inverter with optimal parameters (Kp, Ki, and Kd), PID-PSO enhances HVDC systems stability. By using this method, power flows can be adjusted timely for preserved frequency levels and reliable energy transfer [9]. Power system stability and frequency management for HVDC transmission systems are strong. The work presented in this thesis used ANFIS, ANN, and PID-PSO based control schemes to ensure 50 Hz frequency stability with the special properties of HVDC transmission. Using ANFIS, ANN and PID-PSO models, it is possible to forecast the system behavior and make the HVDC transmission system run steadily and reliably.

1.1 | How Power System Stability Should Be Maintained in HVDC Transmission System

The electrical power system requires balance even when the system is disrupted or changed. By keeping the system within the safe operating parameters it lower the probability of voltage collapse, frequency variation, and blackout. The power system has to be stable for the grid to operate reliably and securely. Two basic sub types of power system stability are [10] stable-state stability and dynamic stability. Steady state stability or load flow stability represents the ability of the power system to maintain an optimum operating condition under normal (i.e., steady state) condition. It ensures that currents and voltages remain within limits and power is well balanced over all the parts of the grid. It is usually assumed that a steady state stability is investigated. Load flow analyses [11] are often used to study steady-state stability in order to verify that the system can meet demand with voltage and frequency stability. The changes like disturbances include faults, load fluctuations, or a sudden loss of generation is the subject of dynamic stability, on the other hand. It focuses on the system's capacity to continue operating steadily and regain state back from momentary interruptions [12]. In order to keep the grid stable overall and prevent a cascade breakdown of the electrical system, frequency stability is essential [13]. Any variation from the required frequency might cause an imbalance in the grid, which can result in blackouts. The frequency is the main parameter that is utilized to balance the power demand and supply in the grid. Therefore, keeping a constant frequency is essential for preserving the power system's dependability, safety, and efficiency. However, number of studies is available in literature on HVAC transmission system, none of the study incorporated the HVDC transmission system. In this regards, this work used a frequency controllers such as ANFIS, ANN, and PID-PSO to regulate the frequency of an HVDC transmission system [14]. For HVAC system, it is possible that the transmitted power may be changed by the controller to keep the frequency within set bounds and reduce very low frequency vibrations [15]. Various control strategies and protection plans are used to guarantee the stability of the power system. Automatic generation control (AGC) modifies the generators' output in real-time to fit demand and control system frequency. Generator terminal voltage is maintained within acceptable bounds using excitation control devices. Small-signal stability is improved and oscillations are dampened using power system stabilizers (PSS) [16]. To preserve stability and avoid cascade failures during emergencies, load shedding schemes disconnect certain loads. Power system stability in HVDC transmission system is a complex and ongoing challenge due to the increasing integration of renewable energy sources (RES), the growing complexity of the grid, and the ever-changing demands of modern society. To improve power system stability and guarantee the grid's dependable operation, system operators, engineers, and researchers are always working to create novel control methods, predictive analytics, and improved monitoring tools.

A stable power system is necessary for a dependable and secure electrical grid. It includes transient stability as well as steady-state stability and small-signal stability [17]. The power system can resist disturbances, maintain voltage and frequency stability, and recover from transient occurrences using a variety of control methods and protection mechanisms. Technology advancements and ongoing research are essential for enhancing power system stability in the face of changing demands and constraints.

1.2 | Study Research Gap and Motivation

Previously, the research was focused on frequency control in HVAC transmission systems using traditional methods along with it, many studies focuses on improving the quality of current and voltage converters in HVAC and HVDC transmission systems. However, our current research aims on improving frequency control at Inverter station in HVDC transmission system by implementing advanced algorithms like ANN, ANFIS, and PID-PSO. The key difference lies in the advancement of these modern algorithms, which enable more precise and efficient frequency control compared with conventional methods. HVDC systems allow for the interconnection of asynchronous AC grids that operate at different frequencies. This capability is essential for enhancing the stability and economic operation of power systems, as it enables power exchange between networks that would otherwise be incompatible due to frequency differences. By facilitating this interconnection, HVDC helps prevent cascading failures and enhances overall grid reliability. The fast response capabilities of HVDC systems contribute significantly to dynamic stability. The control mechanisms in HVDC can quickly adjust to changes in load or generation, stabilizing the network during disturbances. Features such as power swing stabilization and frequency limit control are integral to ensuring that the system can adapt effectively to varying operational conditions, thereby enhancing overall grid stability.

1.3 | Study Challenges

Frequency control in power systems has evolved over the years with conventional controllers on HVAC transmission system, with earlier techniques and their associated drawbacks paving the way for the development of new and advanced technologies such as ANFIS, ANN, and PID-PSO controllers for frequency control in HVDC transmission (after the inverting station). Traditional AC power systems used earlier frequency management techniques that depended on a number of measures to keep the system stable. A typical method utilized governor control, in which the speed of the turbines in power plants was changed to manage the production of electrical power. However, due to the method's primary focus on big generators and its inability to fully address frequency management in a dispersed generating environment, it had certain drawbacks. Another technique utilized AGC systems, which monitored the frequency deviations and adjusted the generation accordingly. AGC systems were effective in restoring system frequency to its nominal value, but they often relied on centralized control and did not account for the dynamic response of the system. Consequently, the response time of AGC systems was relatively slow, leading to potential frequency deviations before the control actions could take effect.

An effective system based ANFIS, ANN, and PID-PSO may be utilized to automatically modulate the frequency in HVDC transmission system at any load (after the inverting station) in order to solve this issue. The adopted technique allows for automatic frequency regulation without manual intervention, resulting in a more cost-effective and efficient system with minimal component utilization. This approach offers improved accuracy, simplicity, and cost-effectiveness compared with traditional methods for regulating frequency.

1.4 | Contribution of the Study

The power system that was being affect due to sudden change in load connected with the HVDC transmission system and may result in blackout, a control system based on ANFIS, ANN, PID-PSO controller is used to tackle the problem. The research objectives are listed below:

- To design and simulate the MATLAB Simulink model of HVDC transmission system connected with the load and observe the effect of changing load on frequency.
- To train ANFIS, ANN, and PID-PSO controllers to maintain the frequency of the system within a desired range of 50 Hz under varying load conditions.
- To validate the performance of the proposed system.

Use of predictive models such as ANFIS, ANN, and PID-PSO to anticipate frequency deviations and preemptively adjust converter parameters to stabilize the grid. Significant reduction in response time to frequency fluctuations compared with traditional control methods. Capability to handle a broader range of frequency variations while maintaining system stability. Ability to manage both over-frequency and under-frequency scenarios effectively. Ability to reconfigure or adapt the control logic in response to faults within the HVDC system. With handling of transient events like sudden load changes, and power surges, without overall system stability being compromised. These energy efficient algorithms optimally schedule switching patterns of the power electronic devices, energy not being lost. Auxiliary power consumption reduced with optimized control strategies. Synchronization and coordination improvement between the HVDC inverting station, which, in our case, is an inverter, and the connected AC grid for frequency regulation. These intelligent schemes, due to their flexible controls, can regulate frequency from the rectifying or inverting sides.

Indeed, recent approaches for frequency control of power systems put emphasis on adaptability and responsiveness to the trend on integration of RES. In addition, these new strategies typically employ advanced control techniques, like fractional order control, to improve stability and lower frequency drop during disturbances. Demand response mechanisms can be introduced to more quickly respond to adjustments in load, using the fast response capabilities of power electronic interfaces. In addition, providing ancillary services for frequency regulation, distributed energy resources such as battery storage and smart electric vehicles are also used. In addition, these methods are robust to uncertainties by using adaptive control strategies that can still achieve the desired performance when the system parameters change. Taken together, these new approaches seek to build a more resilient power grid capable of meeting ever changing supply and demand.

Available methods for frequency control in power systems have many limitations, which are listed below:

- The increasing integration of RES diminishes system inertia, leading to faster frequency fluctuations and instability during disturbances.
- Conventional generators often have slow response times due to mechanical inertia, which can result in significant frequency deviations before corrective actions are implemented.
- There is no universal standard for frequency control across different power systems, leading to inconsistent responses to frequency deviations.
- Many distributed generation units lack advanced frequency control capabilities, complicating the overall management of system frequency.
- Implementing advanced frequency control technologies can incur high costs, affecting the economic viability of power generation projects.
- Frequency deviations beyond nominal levels can damage equipment such as generators and transformers, which are designed to operate within specific voltage-to-frequency ratios.

This paper contains a very important problem of frequency handling in HVDC transmission system when connected with the load. Study significance with problem statement and research objectives are presented in Section 1. Section 2 covers the early and recent developments in the field of HVDC transmission system when handling frequency problems connected with the load. The clear research gap as compared with the published research with novelty is also covered in this section. Section 3 designed the MATLAB model with detailed specification and description of controllers including ANN, ANFIS, and PID-PSO. Section 4 presented the results under the different controllers used and Section 5 covers conclusion.

2 | Related Work on Frequency Control of HVDC Transmission System

2.1 | Early Developments

Effective frequency regulation was clearly needed when towns and industry adopted electrification and networked power networks at the beginning of the 20th century. The integration of synchronous generators into power networks, which required rigorous control to assure stable frequencies, was at the core of this difficulty. This was overcome by early research during the 1920s concentrating on Governor Control Systems (GCS) [18]. These systems kept a steady speed turbine with direct control on the turbine speeds, hence, indirectly controlled the frequency. The evolution of more complex and intellectually sophisticated strategies began about the middle of the 20th century with the building of complex and expensive power networks [19]. The popularity of analog and digital control techniques allowed for more accurate frequency regulation and quicker reaction to changes in demand and supply. With the incorporation of sophisticated computer-based control systems and sophisticated control algorithms, these developments lay the groundwork for contemporary frequency control tactics [20]. Analog and digital control techniques became so popular, that they permitted more accurate frequency regulation, and react rapidly to the changes in demand and in supply. These developments provide the foundation for modern frequency control techniques, based on the application of sophisticated computer based control systems and sophisticated control algorithms. With continued development of the power system with the addition of RES and smart grid technologies, frequency regulation has become an important part of maintaining grid stability and power quality.

2.2 | Recent Developments

The frequency control landscape is seeing a major change due to recent technology advancements and incorporation of RES. Smart grid technology has started to fuse cutting edge sensors, communication infrastructure, and data analytics to transform frequency monitoring and other activities. These parts provide real time monitoring of power system parameter to allow more accurate and adaptive frequency control techniques [18]. The recent progress in this field is discussed below:

This work [21] is performed on an isolated microgrid with vehicle to grid (V2G) integration for the load frequency control (LFC) using ANFIS based controller. It is concluded that the suggested ANFIS controller has superior damping performance and faster settling to frequency changes from tiny disturbances than traditional PID and fuzzy controllers. The practical benefit is that it needs less mathematical intricacies so it can be relied upon a good implementation alternative. And it will only perform as well as the quality of the training data. This work shows that ANFIS controllers can contribute to LFC and system stability within an isolated microgrid.

The latest developments in realistic renewable energy supply (RES) models, sophisticated controllers, HVAC integration, and soft computing optimization approaches are discussed in this study [22] together with current concepts in AGC. The incorporation of RES and the use of intelligent and sliding mode controllers are highlighted as improving system dynamics. Performance comparisons between conventional/deregulated systems with HVDC, FACTS, and energy storage devices (ESD) integration show improved performance, especially with interline power flow controller (IPFC) and redox flow batter (RFB). The deployment of AGC in deregulated electricity networks and associated difficulties are highlighted in the paper. Overall, it demonstrates substantial advancements in AGC/LFC, including RES integration, cutting-edge controllers, and optimization methods that improve system performance and stability.

This study [23] suggested that frequency regulating methods for voltage controlled coordinated (VSC) HVDC integrated wind power production systems. It illustrates the great relevance of wind turbines and of VSC HVDC for frequency stability as wind power penetration increases. Wind turbine frequency support using energy storage system is investigated and it presents techniques in organizing wind turbine for frequency support. Encouragingly, the adaptive frequency response (AFR) method is also found to work particularly well. The key idea is highlighted that rotor speed recovery should be seriously factored in when designing wind turbines to avoid severe frequency nadir.

This research [24] compares the different controllers efficiency by how they work using MATLAB/Simulink tools. The study also shows that ANFIS is the best performing controller among those considered, with the shortest settling time and percentage overshoot. Simulation results are used to prove that the proposed new method significantly improves controller performance. This practical discovery is also of enormous potential in improving control systems for many applications, with more reliable, effective functioning in practice.

In a nonlinear linked power system, this research [25] studies intelligent controller strategies for LFC in a nonlinear linked power system. Comparing ANFIS-PID and Fuzzy-PID controllers with traditional PID controllers, it shows considerable gains in dynamic responses for a two-area system. The installation of a superconducting magnetic energy storage (SMES) unit enhances performance of the system. The performance of the suggested controller is confirmed by AGC with unified power flow controller (UPFC) and sensitivity analysis that proves the robustness of the controller. The study achieves an effective LFC controller, particularly with the SMES integration, to enhance the system performance and stability under different situations.

These studies [26, 27] the AGC of a hydroelectric facility is explored by using PID, FLC and ANFIS controllers. ANFIS showed a better than other controllers in terms of lowering frequency deviations under step load disrupts and quicker system recovery. This study highlights the importance of state of the art control methods for maintaining power quality and grid stability of coupled systems. Future research will also be undertaken to identify AGCs for use in contrast with automated voltage regulators in efforts to improve performance. The work consists of showing the effectiveness of ANFIS on aiding the improvement of the power system operation and also the inferences gained on the AGC problem optimization for hydropower projects.

Based on voltage source converters, this research [28] performed in depth analysis as it concerned control methods for VSC-HVDC systems. The VSC HVDC offers the benefit of open and adaptable controller design that enables system performance and parameter choices to improve. The shortcoming of a conventional voltage control system with no separate regulation of active and reactive power is overcame through the application of Advanced Voltage Control Coordinated (VCC) and Phase Locked Loop (PLL)-free Power Synchronization Controller (PSC) technologies. In offshore wind farms, adaptive back-stepping controllers on VSC-HVDC are employed for voltage droop management in failures. Optimized PI controllers improve stability, but may increase expenses and the chance of commutation loss. Furthermore, providing more study on VSC HVDC for large applications with various voltage and power levels is advised.

An intelligent and distributed ANFIS-PI controller based secondary control technique for microgrids is proposed through the research [29] In contrast to typical fixed PI controllers, the ANFIS technique controls uncertainty and load variations by making the controller coefficients adaptive to microgrid circumstances. For each distributed generator (DG) it has independent decentralized control, making use of regional communication networks and local unit controllers to generate control signals for regional primary controllers. It is shown on a microgrid system that the proposed methods improve voltage and frequency correction and decrease steadystate errors. It appears that with this approach the intelligent control of the microgrid has the capacity to boost performance and stability of the microgrid under dynamic load circumstances.

These studies [30, 31], It is concluded that a Deep Reinforcement Learning (DRL) method to self-tune controller parameters in a hybrid AC and multi terminal DC grid power system. Under different operating conditions, the proposed method improves frequency support. The effectiveness of the DRL based agent is demonstrated with a MATLAB/Simulink model. DRL will perform similar to the traditional methods under light transmission load, but significantly better than the traditional methods under heavy load conditions. Training with many operational conditions enables the agent to adapt to many scenarios. The work presented in this thesis contributes to intelligent control strategies in power systems, where DRL is used to optimize controller parameter tuning and to improve frequency regulation in hybrid AC and multi terminal DC grids.

This study [32] proposes a frequency regulation strategy using variable-parameter fuzzy logic controllers (FLC) during black starts in power systems. Optimal FLC parameters ensure equal maximum frequency deviations at the rectifier and inverter sides. The difference between actual and optimal FLC parameters shows a linear relationship with the deviation difference between rectifier and inverter sides. Additionally, the deviation values change linearly with system capacity and near-linearly with generator parameters. The proposed strategy coordinates frequency deviations, allowing maximum load application within limits during black starts, improving system recovery, and frequency stability. This research provides insights into adaptive FLC control strategies for power systems during challenging operational conditions.

This paper [33] presented a communication free coordinated control strategy for multi terminal VSC HVDC systems are proposed to handle power sharing and frequency stability in weak AC systems. Support of bidirectional active power between DC and weak AC systems is enabled by the strategy. Flexible power allocation is found to reduce DC voltage fluctuation and to alleviate voltage errors' effects in power regulation. The weak AC system is provided with active power support from DC system by limiting converter station output to maintain frequency stability. By allowing some frequency quality to be sacrificed, for the price of providing short term power support for HVDC system, the ability to maintain multi terminal VSC HVDC system stability is achieved. The results found in this research will provide knowledge for improving the power systems performance without communication between converter stations.

This paper [34] then investigates the use of HVDC systems to supply frequency response control in under 1 s, in power system disturbances. Direct use of HVDC response characteristics may not be fully exploited in traditional frequency response control. A fast frequency response control using VSC-HVDC systems based on a multivariate random forest regression (MRFR) algorithm is proposed. Unlike frequency deviation tracking, MRFR control utilized to HVDC maximizes fast response and can provide fast power support during disturbances, stabilizing the system. The simulation results sustain that account for the proposed MRFR based control, frequency low points are improved and system stabilized during events. The potential of machine learning based frequency response estimation to improve performance of HVDC in power system operations is shown.

A multi objective optimization algorithm for the dead band parameters of FLCs in DC systems is proposed in this research [35], the objective is to increase transient frequency and ensure stable DC system performance. Using the on dominated sorting genetic algorithm method, the ideal dead band parameters for DC FLC are obtained. Simulation results show that the proposed approach simultaneously reduces both the system frequency deviation and the number of FLC operations while providing a useful means to select FLC dead band values and improve power system stability.

This work [36, 37], a whole state feedback control strategy of AGC regulator design for a deregulated power system is proposed. Both study a three area linked power system with non-reheat turbines, with and without a parallel HVDC transmission connection. The suggested controller's efficiency is shown by dynamic response plots that illustrate the system's behavior in various situations. A PID controller and an ANN controller are compared. We compare the two methods and show that the ANN controller outperforms in terms of AGC and its results provide guidance regarding better power system stability and regulation as well as improved AGC techniques for deregulated power networks, especially linked networks with different transmission.

This study [38] offers a unique method to improve the dynamic performance of voltage source converter (VSC) stations. The study simultaneously adjusts the control settings of the inner current control (ICC) and outer current layer PI (OCLPI) controllers using a multi-objective optimization approach based on PSO. The ideal VSC dynamic behavior is what this optimization seeks to attain. Through PSCAD simulations, the efficacy of the suggested method is assessed on a four-terminal VSC-HVDC test grid. A comparison is made with traditional optimization techniques. Scenarios such load demand variations, changes in wind energy, and VSC disconnections are all thoroughly examined in the research.

Previously, the research was focused on frequency control in HVAC transmission systems using traditional methods along with it, many studies focuses on improving the quality of current and voltage converters in HVAC and HVDC transmission systems. However, our current research aims on improving frequency control at Inverter station in HVDC transmission system by implementing advanced algorithms like ANN, ANFIS, and PID-PSO. The key difference lies in the advancement of these modern algorithms, which enable more precise and efficient frequency control compared with conventional methods. This research aims to enhance the adaptability and intelligence of HVDC system to meet the complex demands of modern power grids.

3 | Materials and Methods

Modern power networks place a high priority on the efficient and reliable functioning of HVDC transmission systems, particularly given the rising need for dependable clean energy. Controlling system frequency is crucial for guaranteeing uninterrupted power delivery. Frequency fluctuations can cause power supply interruptions, which can compromise the grid's overall stability. The current study is investigating the creation and use of an intelligent frequency control system at the inverter station inside HVDC transmission networks. This study intends to improve frequency stability in HVDC transmission systems by merging ANFIS, ANN, and PID-PSO approaches. The block diagram of the proposed system is given in Figure 1. The methodological flow of this study is shown in Figure 2 and covers the development of simulation models, controller training, system validation, and performance evaluation. The approaches used to deal with the intricate dynamics of frequency regulation within HVDC transmission, paving the way for a more dependable and effective energy transmission environment.

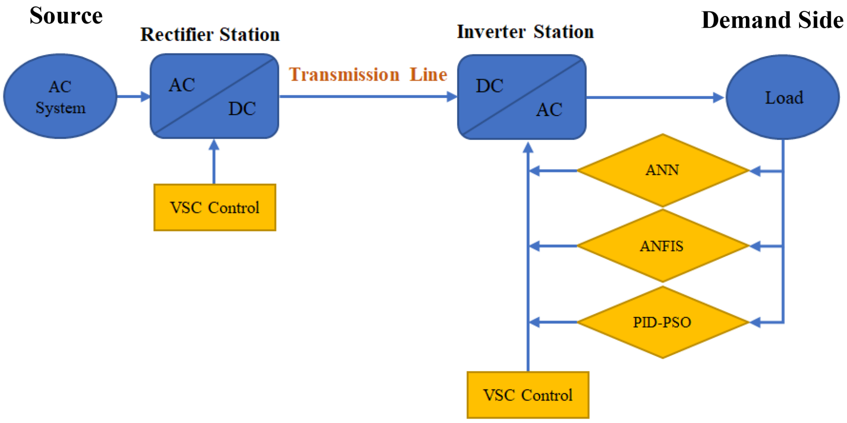


FIGURE 1 | Block diagram of the system.

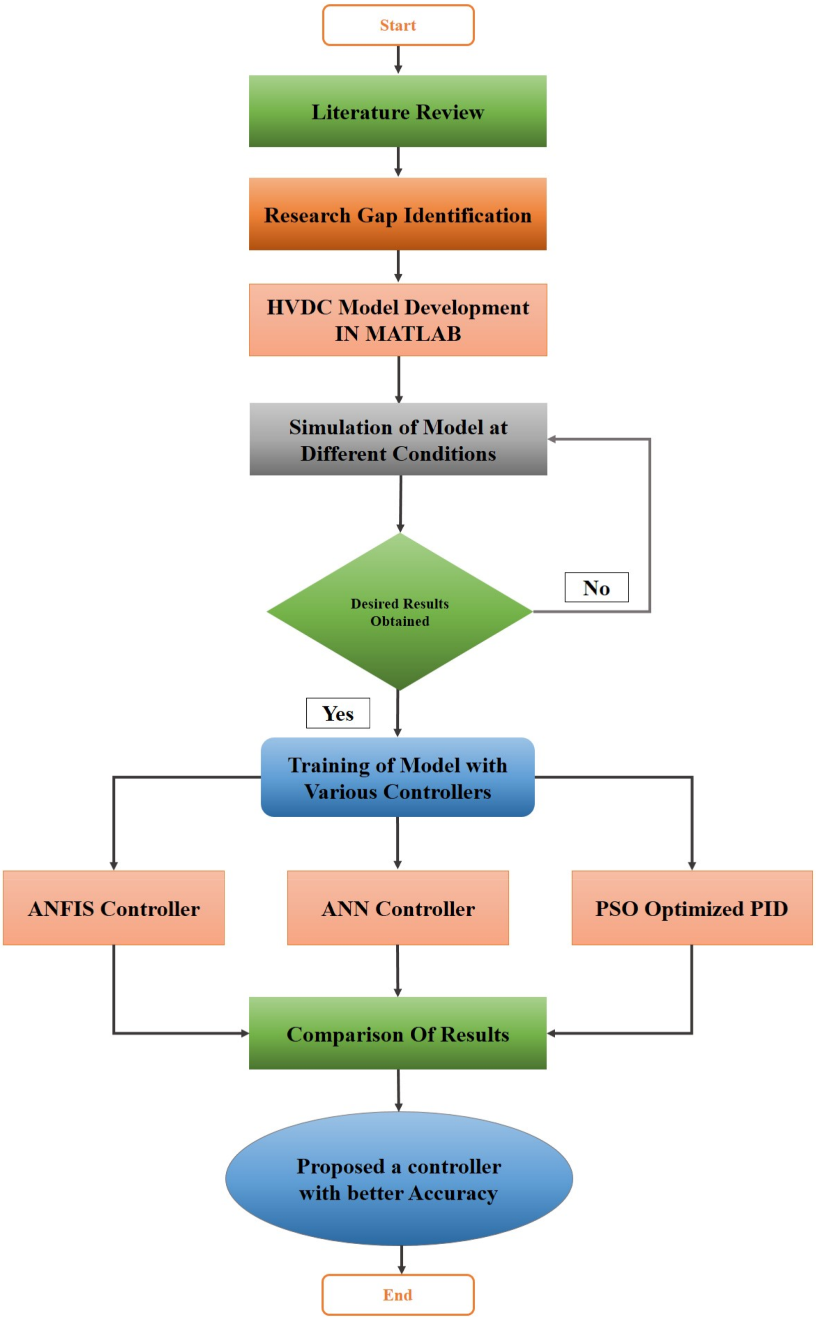


FIGURE 2 | Methodological flow diagram of the system.

3.1 | HVDC Transmission System

Modern power grids now rely on highly effective HVDC transmission methods to transport power across large distances. The HVDC system, in contrast to conventional AC systems, makes use of the direct current concept, which reduces energy loss by obviating the necessity for frequent AC-DC conversions [39]. A switching station, power electrodes, transmission media, and an advanced control and protection system are the fundamental parts of an HVDC system. The central component of an HVDC system, converter stations transforms alternating current into direct current at the transmitting station before reversing the process at the receiving station. The source electrodes, which are often buried in the ground or immersed in water, offer a channel for direct current, assuring its efficient and safe passage. The selection of the transmission medium, which might include overhead cables, subterranean cables or both, is influenced mostly by distance and environmental concerns. Control and protection systems, which painstakingly monitor parameters and swiftly modify converters to ensure grid stability against disruptions, are at the core of steady and dependable operation. The single line diagram of HVDC system is given in Figure 3 [40, 41].

A variety of advantages that HVDC transmission systems provide encourage its acceptance and wide-scale implementation. In particular, across long distances, HVDC systems exhibit greater efficiency, resulting in much lower transmission losses

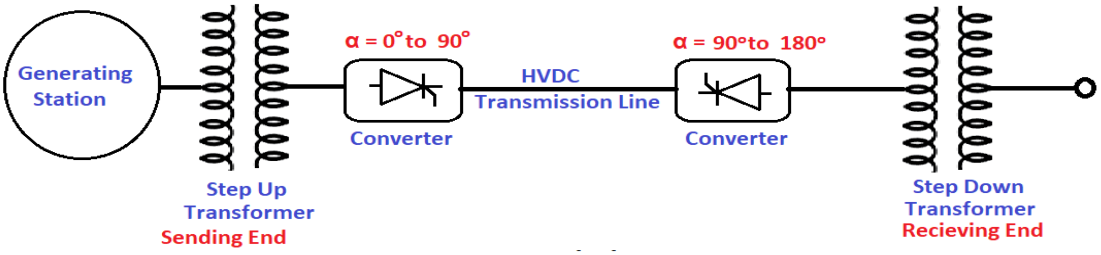


FIGURE 3 | Single line diagram of HVDC transmission system.

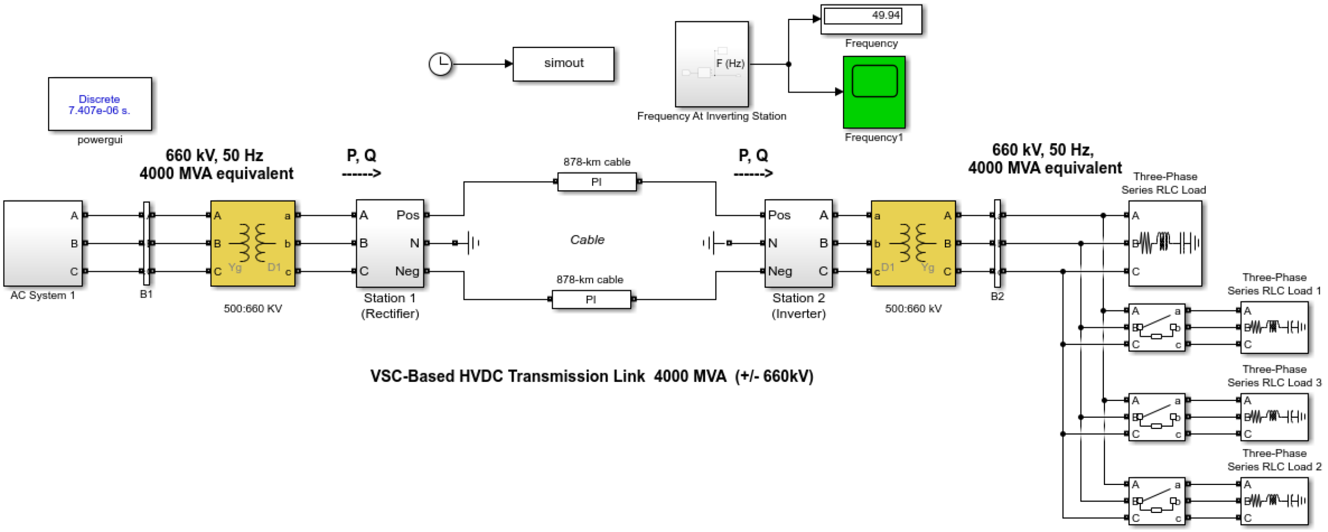


FIGURE 4 | MATLAB model of HVDC transmission system.

than AC systems. As a result, there is less energy wasted and substantial cost savings, which makes them more desirable then HVAC transmission systems. HVDC systems is successfully cover the enormous geographical boundary which is demonstrated by its ability to link transcontinental power networks or install underwater cables between islands. In addition to these achievements, HVDC systems contribute to the grid's overall stability. Large-scale blackouts and disturbances are less likely because to more stable power supply, which is enhanced by clear current regulation and rapid reaction to grid disturbances.

In addition, the proliferation of RES in the global energy landscape has prompted the integration of HVDC technology to address specific challenges in the distribution of green energy. Offshore wind farms, often located in remote locations with abundant wind resources, can efficiently transmit the generated electricity to densely populated urban centers via HVDC transmission. This integration not only helps to maximize the use of renewable resources, but also accelerates a broader transition to cleaner, more sustainable energy landscapes. HVDC's role in improving the grid's ability to assimilate RES underpins global efforts to mitigate climate change and reduce carbon emissions [42].

In addition to its technological advantages, HVDC technology has real environmental advantages. By using an HVDC line, electromagnetic interference is kept to a minimum, possible damage to delicate electronic equipment is restricted, and electromagnetic compatibility is ensured. Additionally, HVDC systems might lessen the need for lengthy overhead transmission lines, which helps to reduce visual effects on the surrounding environment and wildlife habitat. A further option for linking islands or regions divided by water bodies is the deployment of underwater cables, which can be made possible by HVDC.

The HVDC transmission system represents a breakthrough in power transmission technology. By harnessing the inherent efficiency of DC transmission, HVDC systems present a reliable and efficient path for power transmission over large distances. Through the synergy of powerful switching stations, power electrodes, transmission media, and control systems, HVDC technology enhances network stability, improves efficiency, and seamlessly integrates network components.

3.2 | Model Description

In this section, a concise overview of the model architecture and its components is presented. Research into the design choices is very important that underpin its functionality and explore the key features that contribute to its performance. The MATLAB model of HVDC transmission system is given in Figure 4. This section sets the stage for a comprehensive understanding of our model's complicated workings.

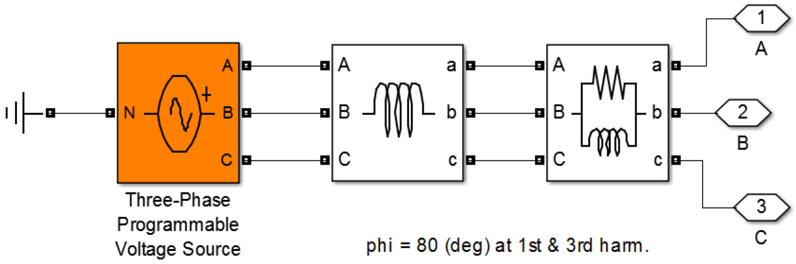


FIGURE 5 | Design of AC power source in MATLAB model.

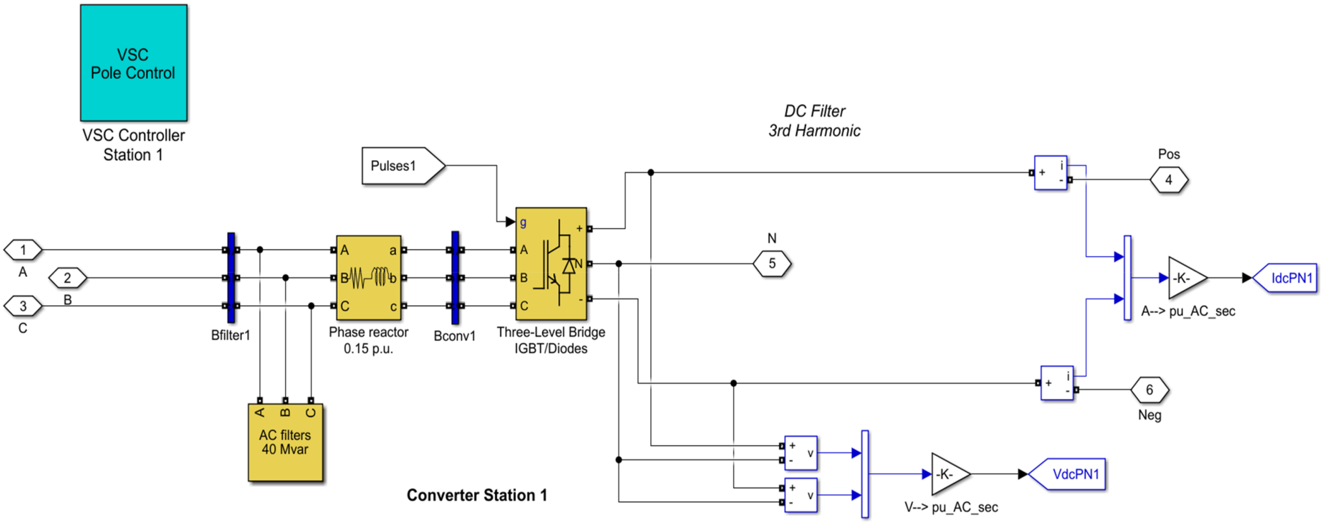


FIGURE 6 | Design of converter station in MATLAB model.

A 500 kV, 4000 MVA, 50 Hz system transmits electricity to another similar AC system via a forced-commutated, VSC connector with a capacity of 4000 MVA (±660 kV DC). Three-level neutral point clamped (NPC) VSC converters utilizing near insulated gate bipolar transistor (IGBT) or diodes in the rectifier and inverter. Using a single-phase triangle carrier wave with a frequency of 27 times the fundamental frequency (1350 Hz), sinusoidal pulse width modulation (SPWM) switching is performed. The converter reactor, step-down Yg-D transformer, AC filters, and converters are all included in the station along with the converters. The capacitors and DC filters are also included. The saturation characteristics and transformer tap changers are not emulated. The two dominant harmonics are high-pass tuned into the 40 Mvar shunt AC filters at the 27th and 54th positions. The 0.15 p.u. converter reactor and 0.15 p.u. transformer leakage reactance enable control of converter active and reactive power output and allow the VSC output voltage to shift in phase and amplitude with respect to the AC system point of common coupling (PCC) (bus B1 for station 1 and B2 for station 2). The VSC terminals are linked to the reservoir DC capacitors. Both the system dynamics and the DC side voltage ripple are impacted by them. The principal harmonic present in the positive and negative pole voltages, and to which the high-frequency blocking filters are tuned, is the third harmonic. The rectifier and the inverter are interconnected through a 878 km cable (i.e., 2 pi sections) and two 8 mH smoothing reactors. The detailed description of each type of component of HVDC transmission system is given below:

- *AC System*

An HVDC transmission system's journey starts with the generation of electrical energy through conventional power plants. These power plants generate energy using a range of fuels, including fossil fuels (coal, natural gas), hydroelectric dams, nuclear reactors, or renewable sources (wind, solar). AC, which exhibits cyclical oscillations between positive and negative voltage levels, is the kind of energy that these power plants produce. The primary power source for the whole HVDC system is this alternating current. Figure 5 presented the representation AC power source in MATLAB.

- *Converter Station*

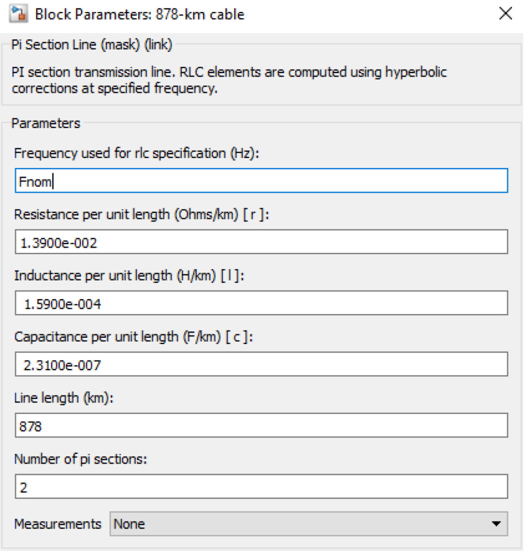
Alternating current is sent to the converter station from the transmission end of the HVDC system. This station is a key component outfitted with cutting-edge power electronics, or transducers. These converters make it easier to change AC into DC. They are often based on an IGBT or thyristor. The AC waveform is rectified during this operation, thereby turning it into a DC of charge. The conversion process may be precisely controlled by using an IGBT or a thyristor, resulting in a steady, regulated, and effective DC output for long-distance transmission. Figure 6 shows the representation of converter station in MATLAB.

- *HVDC Transmission Line*

The DC power will be sent over the HVDC transmission line after the AC to DC conversion is finished at the transmission end. It is possible for DC current to flow over long distances with little energy loss because to this line, which serves as its physical conduit. The transmission distance, regional terrain, and environmental issues all have a role in the transmission medium selection. Overhead cables, subterranean cables, and even submarine cables can be used to establish HVDC transmission lines for underwater transmission. The reduced resistance loss of the DC line as opposed to the AC line is an intrinsic characteristic that increases efficiency over long distances. The parameters for HVDC transmission system is set in the MATLAB model and shown in Figure 7.

- *Inverter Station*

The inverter station receives the DC electricity when it reaches the HVDC transmission line's receiving end. The inverter station has converters that aid in the conversion process, much like the transmission head does. AC is created here by reversing DC. The converter carefully modifies the DC waveform to mimic the original AC waveform, often using an IGBT or thyristor. With the help of this procedure, the existing AC grid's needed voltage, frequency, and phase characteristics are met by the AC power generated at the inverter station. The design of inverter station in MATLAB model is shown in Figure 8.


Block Parameters: 878-km cable

Pi Section Line (mask) (link)

PI section transmission line. RLC elements are computed using hyperbolic corrections at specified frequency.

Parameters

Frequency used for rlc specification (Hz): Fnom

Resistance per unit length (Ohms/km) [r]: 1.3900e-002

Inductance per unit length (H/km) [l]: 1.5900e-004

Capacitance per unit length (F/km) [c]: 2.3100e-007

Line length (km): 878

Number of pi sections: 2

Measurements: None

FIGURE 7 | HVDC transmission line parameters in MATLAB model.

- *ANFIS Controller*

The ANFIS controller for frequency control uses a dynamic procedure to manage an inverter's output frequency by modifying the firing angle of the triggering pulse in response to variations in load. The design of ANFIS controller is shown in Figure 9 and a detailed explanation of the terminology is given Table 1.

- *ANN Controller*

An ANN controller for frequency control uses a dynamic method to manage an inverter's output frequency by modifying the firing angle of the triggering pulse in response to variations in load. The design of ANN controller is shown in Figure 11 and a detailed explanation of the terminology is given Table 2.

- *PID Controller through PSO Optimization*

PSO based algorithm is used to optimize the parameters of PID controller for frequency control in HVDC transmission systems. PSO simulates particle movement in a search space to iteratively optimize parametric values of Kp, Ki, and Kd (PID controller). PID-PSO improves stability in HVDC systems by modifying the inverter's operation depending on optimal parameters (Kp, Ki, and Kd). PSO is a nature-inspired optimization algorithm used to find optimal solutions in complex search spaces. When applied to frequency control in power systems, PSO optimizes control parameters to regulate the frequency. Here is a step-by-step breakdown of its working. The design of PID-PSO controller is shown in Figure 14 and a detailed explanation of the terminology is given Table 3.

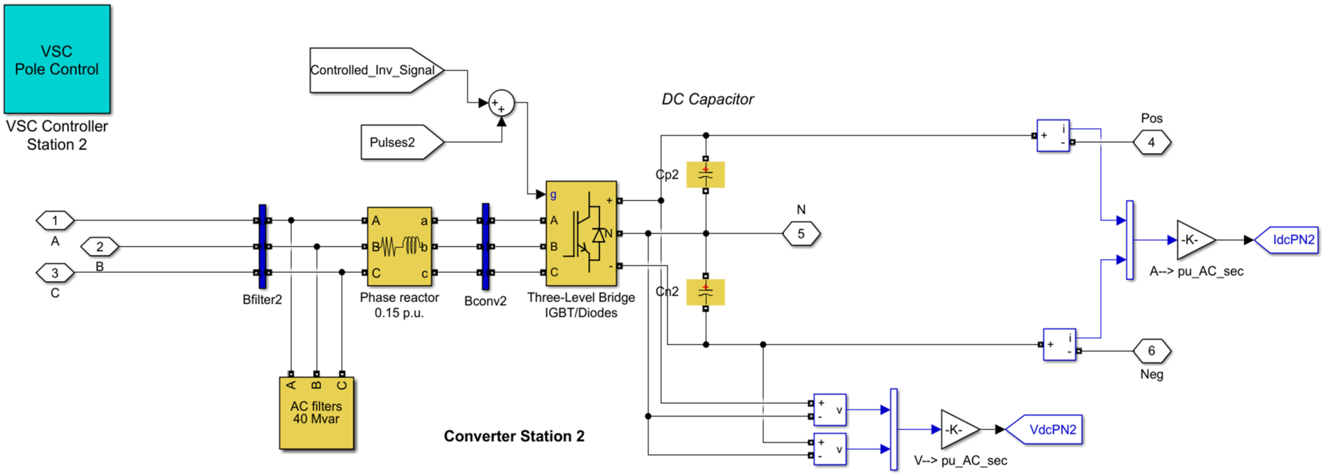


FIGURE 8 | Design of inverter station in MATLAB model.

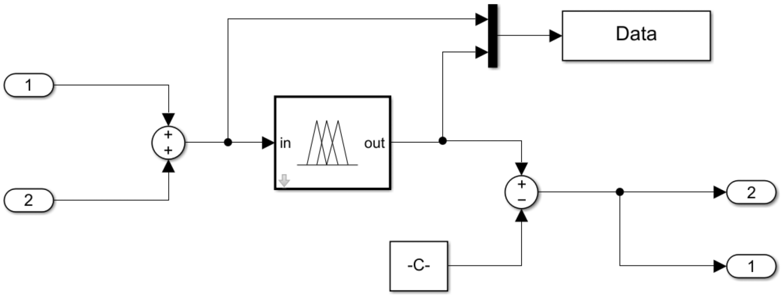


FIGURE 9 | Design of ANFIS controller in MATLAB model.

TABLE 1 | Parameters description of ANFIS controller.

Parameters	Description
Frequency control with firing angle adjustment	The fundamental goal of the ANFIS controller is to keep an inverter's output frequency within a predetermined range, regardless of changes in the system's load. The ANFIS controller modifies the firing angle to achieve this frequency control, which controls the timing of the inverter's output pulses. The ANFIS controller determines the ideal firing angle necessary to mitigate the effect of the load change on the output frequency when the load on the system grows or decreases. Two key signals are fed into the input of ANFIS controller: a. Output Frequency Signal from the Inverter: The inverter sends the real output frequency signal to the ANFIS controller. Real-time information regarding the system's current frequency is provided via this signal. b. Reference Signal of 50 Hz: The ANFIS controller additionally receives a second reference signal that is provided at a reference frequency of 50 Hz (or any other desired reference frequency). The target frequency level is measured against this reference signal.
ANFIS processing	The ANFIS controller additionally receives a second reference signal that is provided at a reference frequency of 50 Hz (or any other desired reference frequency). The target frequency level is measured against this reference signal. The flow diagram of ANFIS processing is shown in Figure 10.
Controlled signal generation	The ANFIS controller creates an output signal that specifies the necessary adjustment to the firing angle based on the input signals and their processing. This regulated signal is calculated to make sure that load changes do not affect how closely the inverter's output frequency stays at the reference frequency (e.g., 50 Hz).
Adjustment of triggering pulse	The inverter receives the regulated signal produced by the ANFIS controller. This signal tells the inverter how to adjust the triggering pulse (firing angle) for the desired frequency control and the change in load. The ANFIS controller successfully adjusts the triggering pulse's time in order to control the inverter's output frequency.
Achieving controlled frequency output	The inverter's output frequency is carefully regulated as a consequence of the ANFIS controller's ongoing modifications to the firing angle based on in-the-moment load variations and the reference signal. Even in the face of shifting load circumstances, the ANFIS controller makes sure that the output frequency stays relatively near to the required reference frequency. This helps the HVDC transmission system's frequency regulation be steady and dependable.

3.3 | Three Phase AC Load

The three-phase AC load may now receive the AC power generated at the inverter station. Three-phase AC charging is an example of the wide range of end users, sectors, and uses that rely on AC power. Everything from homes and businesses to factories and public infrastructure is included in this payload. The AC power supply for three-phase loads complies with strict AC grid standards, keeping synchronous frequency and voltage constant. By ensuring that the transmission power source is fully linked into the current grid, this seamless integration helps to provide a steady and uninterrupted supply of electricity. Table 4 depicts how frequency variations are monitored with respect to the change in load. To start, a large electrical load was introduced to the power system of 2500 MW, keeping the frequency consistent at 50 Hz. Yet, at 0.13 s later a further demand of 500 MW was introduced, which visibly changed the frequency to 49.3 Hz. Due to these fluctuations in load, the system adapted to the additional demand very quickly showing that it is capable of tolerating additional load. The load was reloaded back to its initial level of 2500 MW by 0.34 s causing the frequency to rebound back to 50.8 Hz. At 0.72 s, a reduced load of 1500 MW was introduced, and the frequency surged heavily to 52.2 Hz.

4 | Results and Discussion

The implication of an intelligent frequency control scheme at the inverter station in HVDC transmission system for increasing the stability and efficiency of HVDC power transmission in modern energy network. In this section, we present extensive research, simulations, and experiments that confirm the effectiveness of the proposed ANFIS, ANN, and PID-PSO based control mechanism. These results show how this study has contributed to solving complex frequency control problems and pave the way for a more flexible HVDC power transmission landscape. The results under unstable frequency conditions, without control, are shown in Figure 16. The graph establishes the frequency oscillations, which further prove the importance of control mechanism. The results show that the lack of stability influence causes frequency behavior to be unstructured, which emphasizes the need for advanced controls to ensure stable and reliable operation in HVDC systems. Such conditions necessitated an ANFIS, ANN, and PID-PSO based optimized controllers to regulate frequency fluctuations. Implementation of these ANFIS, ANN, and PID-PSO based optimized control mechanism, promises to suppress these oscillations and provide a constant, controlled frequency output, which will increase the stability of HVDC transmission system.

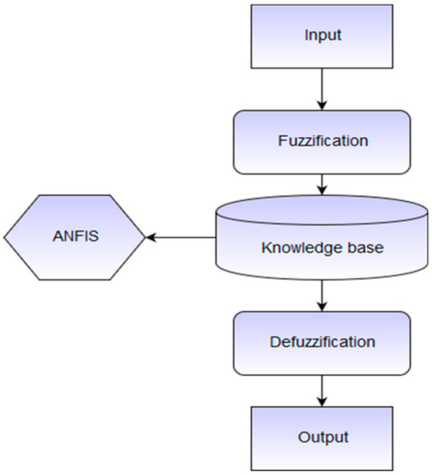


FIGURE 10 | Flow diagram of ANFIS processing.

4.1 | Results With ANFIS Controller

To evaluate the performance of the intelligent frequency control system based on ANFIS, a comprehensive simulation model of the HVDC transmission system was developed in MATLAB model and shown in Figure 17. The model includes AC power supply, converter station, HVDC transmission line, inverter station and three-phase AC load. Parameters such as load variation, 50 Hz reference signal, and ANFIS-controlled signal have been incorporated into the simulation setup to respond like real-world scenarios.

The main purpose of the ANFIS-based control scheme is to adjust the output frequency of the inverter in response to changes in the load. The ANFIS controller effectively adjusted the firing angle, thus affecting the timing of the trigger pulse. Through real-time processing of the actual output frequency signal of the inverter and the 50 Hz reference signal, the ANFIS controller automatically generates the controlled signals. These signals instruct the inverter to vary the timing of the trigger pulses, ultimately keeping the output frequency close to the desired reference frequency even when load conditions fluctuate.

The simulation results shown in Figure 18 and depicted the outstanding efficiency of the ANFIS-based control scheme in achieving precise frequency control. As the load conditions changed, the ANFIS controller cleverly adjusted the firing angle, ensuring that the output frequency remained within the desired range around the reference frequency. The controlled signals produced by ANFIS controlled have depicted the desired results, which shows that the proposed control mechanism used to respond rapidly to load changes and maintain frequency output stable.

In the fast and accurately way, the goal of the ANFIS controller is to balance the system frequency to its nominal value such as 50 or 60 Hz. ANFIS is a hybrid intelligent control system that takes advantage of the reasoning and learning capability of neural networks and fuzzy logic, respectively. Because of its capacity to govern the intricacy and debatability in power generation and circulation, this application is important in power frameworks,

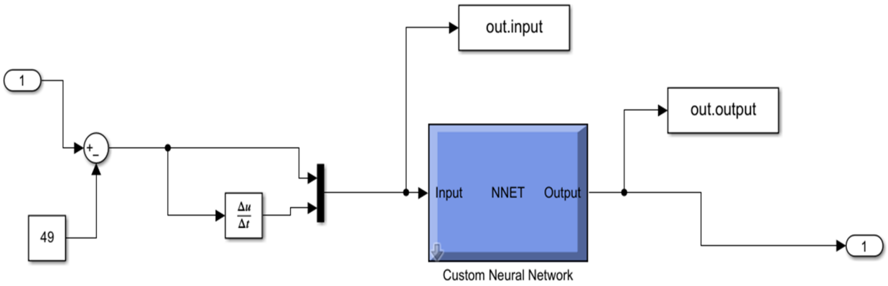
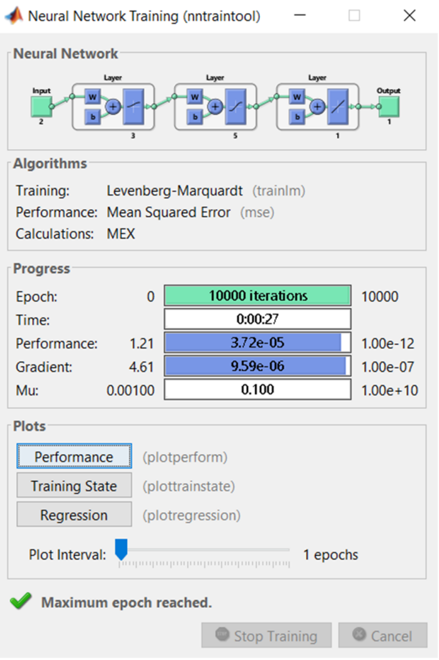


FIGURE 11 | Design of ANN controller in MATLAB model.

TABLE 2 | Parameters description of ANN controller.

Parameters	Description
Input signal reception	The inverter station sends input signals to the ANN that represent the power system's current frequency and the rate of change of frequency. These input signals offer real-time data on the frequency dynamics and load variations of the system.
Historical data integration	Utilizing historical data that encompasses a range of load circumstances and the related control actions, the ANN is trained on MATLAB as shown in Figure 12. The network may learn patterns and correlations between input signal frequency and the best control actions under various load circumstances using this historical data as its starting point.
ANN processing	The input layer of the ANN receives the input signals current frequency and rate of change of frequency. The network's many interconnected layers of nodes (neurons) process the input signals. A weight is allocated to each connection between neurons that controls how much the output of one neuron affects the input of another. Weighted connections and activation functions are used to alter the input signals as they move through the hidden layers. Through the layers, the processed data is gradually refined to capture complex connections between input signals and control operations. The detailed ANN processing is shown in Figure 13.
Output signal generation	The output layer, the top layer of the ANN, generates an output signal that symbolizes the control action required to adjust the frequency of the system. The control action is created using the ANN's learnt knowledge of how frequency changes correspond to efficient control reactions. The ideal modification required in the inverter's triggering pulse to maintain or restore steady frequency is reflected in the control signal generated.
Control signal integration with inverter	The inverter station is then given the control signal produced by the ANN. The received control signal is used by the inverter station to modify its functioning. In order to control the power flow and subsequently the frequency of the power system, it specifically alters the time of the triggering pulse.
Real-time frequency control	The ANN processes the fresh information as the input signals update the current frequency continually and generates control signals in real-time. The inverter's operation is dynamically guided by the control signals to offset frequency variations brought on by shifting loads or other disturbances. As a result of the ANN's capacity to adapt to new situations and learn from past experiences, the power system is kept stable by accurate and prompt control responses.



Training: Levenberg-Marquardt (trainlm)
Performance: Mean Squared Error (mse)
Calculations: MEX

Epoch:	0	10000 iterations	10000
Time:		0:00:27	
Performance:	1.21	3.72e-05	1.00e-12
Gradient:	4.61	9.59e-06	1.00e-07
Mu:	0.00100	0.100	1.00e+10

Performance (plotperform)
Training State (plottrainstate)
Regression (plotregression)

Plot Interval: 1 epochs

✓ Maximum epoch reached.

FIGURE 12 | Training set of ANN controller in the MATLAB model.

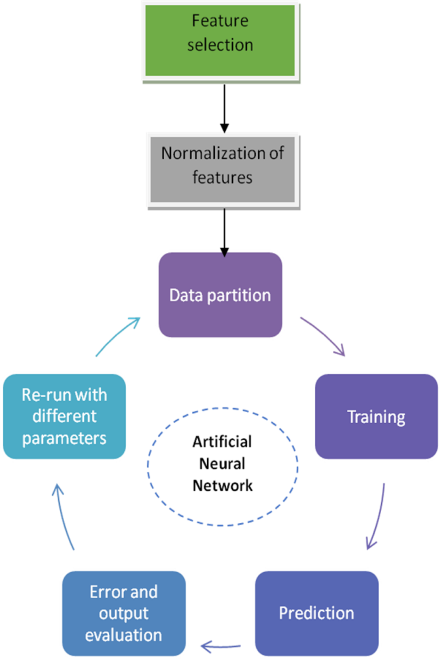


FIGURE 13 | Flow diagram of ANN processing.

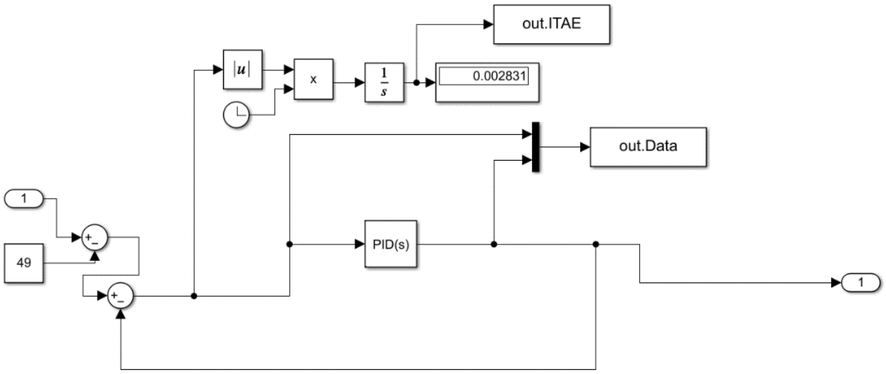


FIGURE 14 | PID-PSO optimized controller.

TABLE 3 | Parameters description of PID-PSO controller.

Parameters	Description
Initialization	Initializing a collection of particles (possible solutions) at random in the search space is the first step in the optimization process. A set of control parameters that affect the frequency control action are represented by each particle.
Improvement process	Using a fitness function, each particle assesses how successfully its control parameters regulate the frequency. Based on their own observations and the best outcomes observed by their neighbors, particles modify their placements.
Optimization iterations	Over multiple iterations, particles continuously adjust their positions and speeds. Both their own best results and the best results of their nearby particles are used to inform their learning. The optimized iterations for the PID-PSO optimized controller is shown in Figure 15.
Convergence to solution	Particles eventually settle in areas of the search space that provide the best control parameter settings for efficient frequency management. The optimal result is represented by the particle with the highest fitness (best control parameter configuration) over all iterations.
Real-time frequency control	The control system can dynamically alter the power flow or other important factors to maintain steady frequency in real-time thanks to the improved control parameter set.

TABLE 4 | Load connected with the HVDC transmission system.

S. no.	Load connected (MW)	Time (s)	Frequency (Hz)
1	2500	0	50
2	3000	0.13	49.3
3	2500	0.34	50.8
4	1500	0.72	52.2

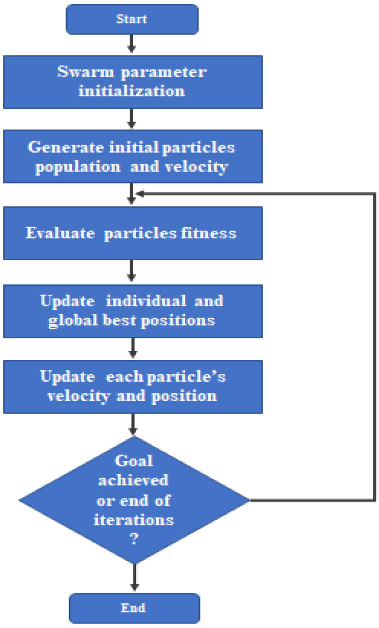


FIGURE 15 | Flow diagram of PID-PSO processing.

particularly for LFC. Balancing between generated power and load demand is performed with the use of designed ANFIS controllers. However, this is essential to system stability, particularly in deregulated power systems where several entities have the ability to impact load and generator dynamics. The variable load conditions are matched using the output of the generators, which are controlled by the controller. The adaptive nature of ANFIS is one of key strengths of this topic. From this historical data it learns and adjusts its parameters in order to improve control performance along the way. Since load patterns can vary arbitrarily, this capability is especially useful for LFC. Traditional controllers can respond to frequency deviations by altering generator outputs, but ANFIS controllers can do so more precisely. Quicker stabilization of frequency is required for reliability of the power system and this is obtained as a result of above.

However, power systems are inherently complex and nonlinear making it difficult to create accurate models to train ANFIS. Due to significant variation in the dynamics of power systems under various operating conditions, it is not straight forward to develop a robust ANFIS model that can generalize across these varying operating conditions. However, ANFIS fails to learn sufficiently well with very little training data. This data can be challenging to

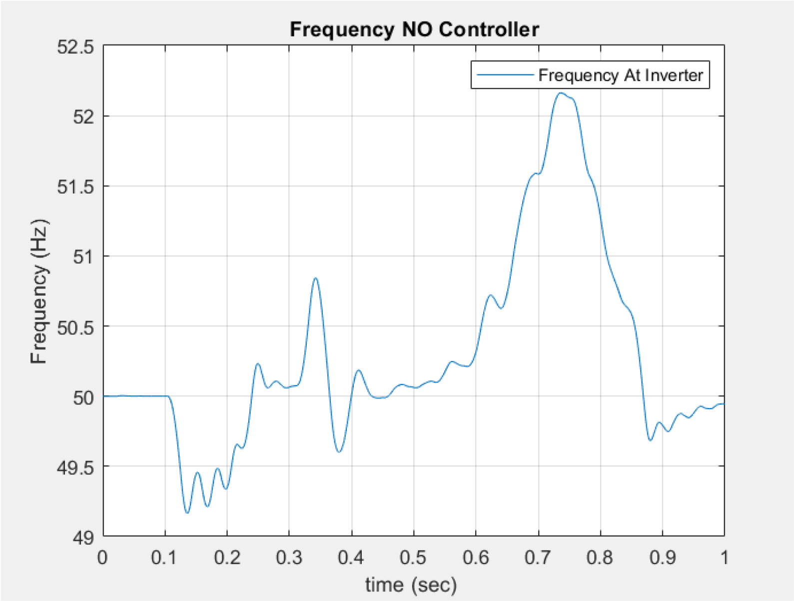


FIGURE 16 | Frequency oscillations without controllers.

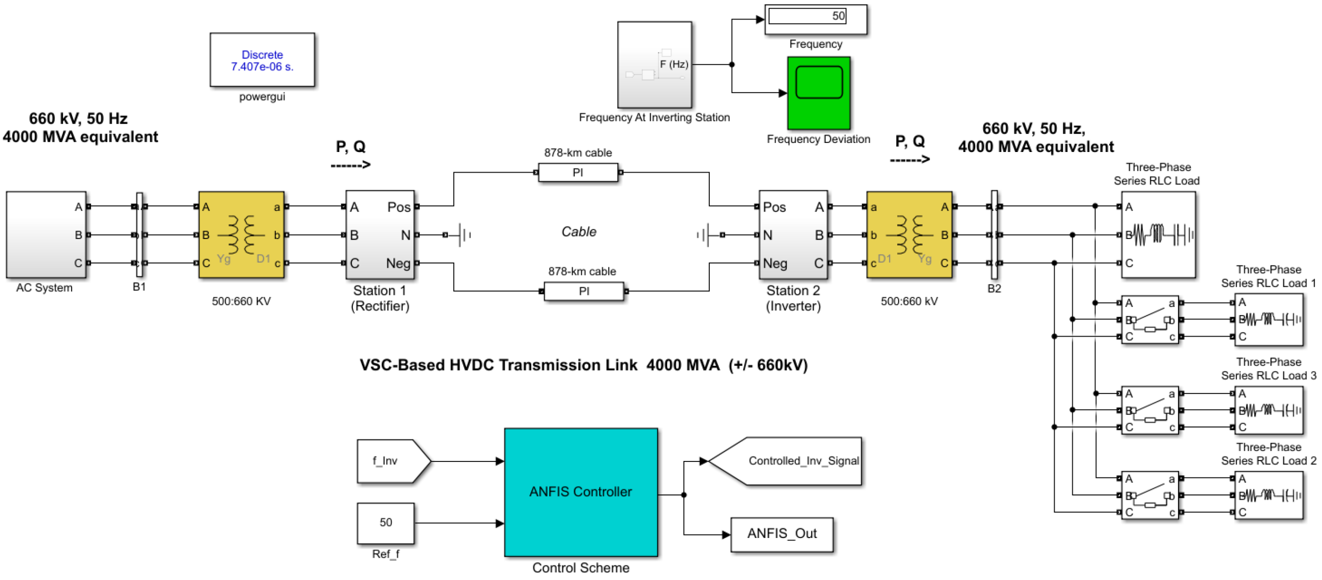


FIGURE 17 | ANFIS based HVDC transmission system.

collect, especially in real time applications where system behavior is being monitored in real time. A poor performance of the systems or inaccurate predictions can result from insufficient or unrepresentative data. The fuzzy membership function design and tuning play a crucial role to the ANFIS controller performance. However, this process can be an exhausting one that is skill dependent, to guarantee the membership functions match the system's behavior. ANFIS training and implementation can have high computational requirements, especially in multiple input–multiple output systems. By inducing delays in response times, this can delay the time required to make such adjustments in the applications such as frequency control, where the response need to be quick enough. The challenge of integrating ANFIS into existing control systems arises in view of the different control strategy and system dynamics they employ. Seamless communication and coordination is necessary for achieving optimal control methodology performance. Uncertainties are common to power systems, which fluctuate in loads, generation from renewable sources, and other external factors. Such uncertainties make it necessary to design sophisticated ANFIS endowed with these capabilities. Real time implementation of ANFIS requires high reliability and stable operation in uncertain situations. However, ensuring the ANFIS controller does not fail during operations is still a fundamental challenge.

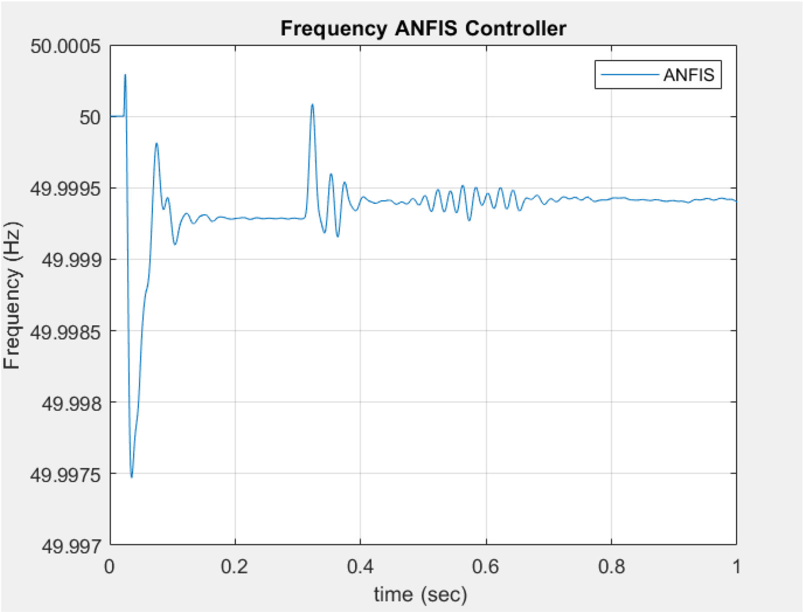


FIGURE 18 | Results with ANFIS controller.

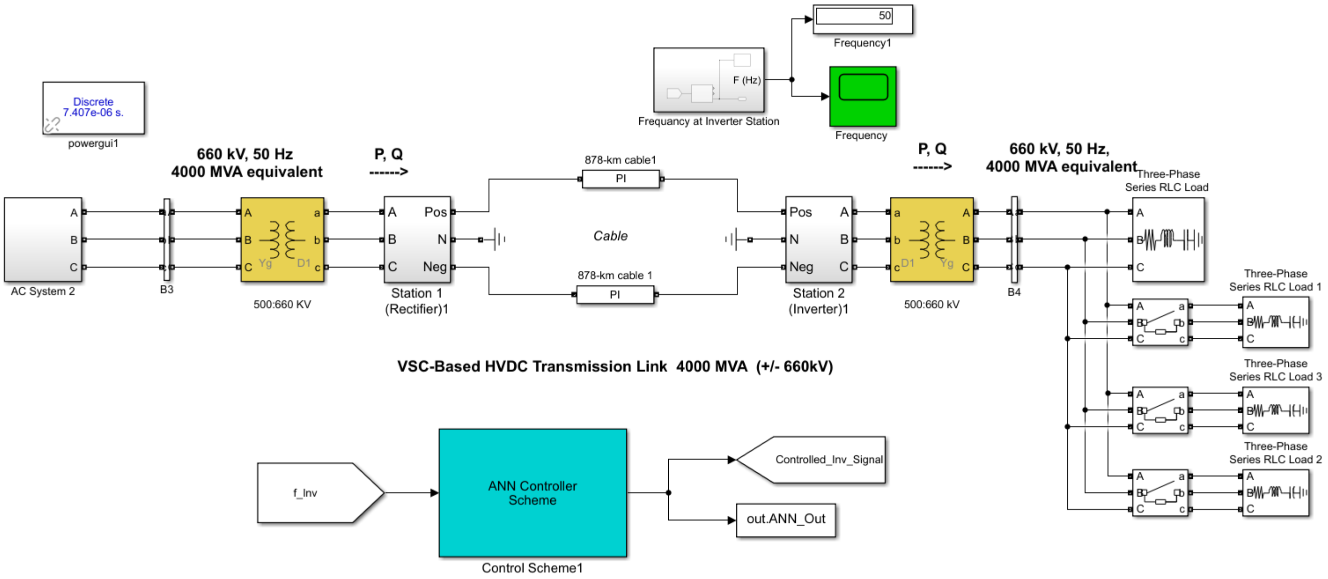


FIGURE 19 | ANN based HVDC transmission system.

4.2 | Results With ANN Controller

The performance of the ANN intelligent frequency control scheme was evaluated using a thorough simulation model for the HVDC transmission system. This simulation model included modeling of an AC supply, converter stations, HVDC transmission line, inverter station and three phase AC load. To simulate the communication bus, load changes, a reference signal of 50 Hz, and control signals produced by ANNs with the MATLAB model shown in Figure 19 were used.

The main goal of the ANN-based control strategy was to efficiently adjust the output frequency of the inverter station in response to load changes. The trained ANN produced precise control signals by properly understanding the real-time input signals indicating current frequency and rate of change of frequency. This signals dictated the modifications that had to be made to the timing of the triggering pulse, which affected how the inverter worked. As a result, even with shifting load conditions, the output frequency was kept very close to the ideal reference frequency.

The effectiveness of the ANN-based control system in attaining exact frequency control was demonstrated by simulation results as shown in Figure 20. At the same time, the ANN controlled modifications to the operation of the inverter kept the output frequency inside the desired range around the reference frequency, whilst load conditions varied. Real time input signals were interpreted by the ANNs and they learned from previous data

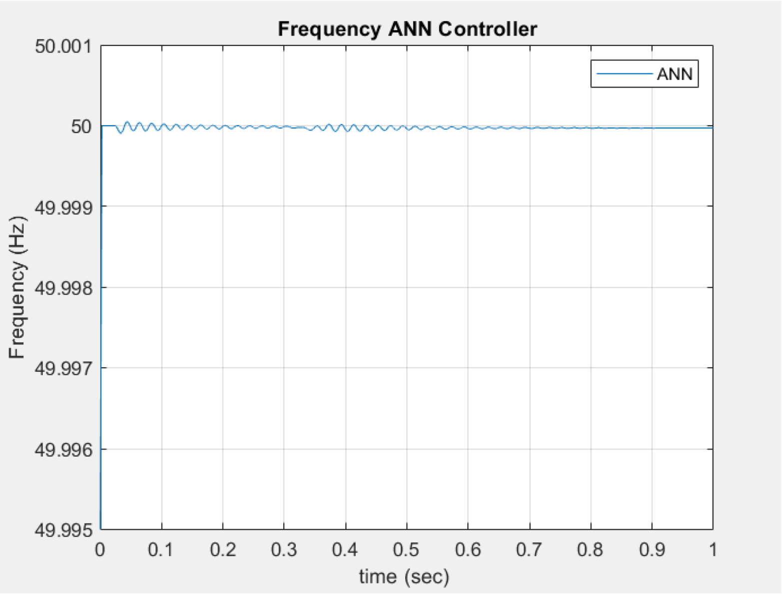


FIGURE 20 | Results with ANN controller.

under dynamic load situations and so generated steady frequency output. From this, we illustrated how adaptable and reliable the proposed ANN-based control system for maintaining grid stability is.

The learning capabilities of ANNs enable them to adapt to different operational conditions and non-linearity within power systems. This flexibility permits them to handle intricate dynamics that fairly challenging for conventional controllers, for example Proportional-Integral (PI) controllers, to perform well at because such controllers are confined to working with linear models. Many applications of ANN controllers are developed based on a model reference approach, such that the ANN is trained to reproduce the behavior of the system as dictated by the desired performance based on the feedback from actual performance. This method improves stability and dynamic performance and it is particularly effective under various load disturbances. ANNs can effectively coordinate multiple generations response for achieving frequency deviations across the nearby interconnected areas in multi area power systems. ANN based LFC has been proven to out-perform the conventional methods such as PID controllers due to its faster response time and smaller steady state error. For the implementation of ANN controllers, the network is trained by using historical data available from the power system. With this training, the ANN learns a mapping between input signals (e.g., such as a load change) and output actions (e.g., such as a generator adjustment) that optimize frequency control. Nevertheless, ANNs have the ability to handle nonlinearities and variation in system parameters without the need of a significant amount of prior knowledge of the system dynamics. According to the research, ANN controllers can improve system performance to a great extent in the form of settling time, overshoot compared with the conventional control strategies. Furthermore, ANNs are able to learn from the past to become robust against the unforeseen disturbances and subsequent power system operational changes.

4.3 | Results With PID Controller With PSO Optimization

The performance of PID controller with PSO optimize for frequency controlling is assessed by comprehensive simulations within the model of HVDC transmission system. This modeling framework contained AC supply, converter stations, HVDC transmission line, inverter station, and three phase AC load. Important characteristics incorporating load changes and performance measurements were added to the simulation system to simulate real world conditions as shown in Figure 21. The goal of the proposed PID-PSO based control approach was to maximize control variables, which directly influence frequency regulation. These parameters were iteratively refined in an iterative fashion by PSO method to yield the "best frequency control" responses. Dynamic adjustments of the inverter station's control settings were made by the PSO method to reduce the frequency deviations, decrease settling time, and limit the overshoots. Results of simulation proved that the PID-PSO strategy is effective to get the exact frequency control. As the system had different load conditions, the PSO algorithm can skillfully modify control settings so as to keep output frequency close to the target reference frequency 50 Hz, as seen in Figure 22.

The PID controller adjusts the output based on three parameters: Proportional gain, instrumental gain, and derivate gain. The purpose of these parameters is to reduce the error in the frequency level that actually occurs relative to the frequency level that is desired in a power system. PSO is an evolutionary computation technique modeled from social behavior patterns of birds and fish. It is an algorithm that optimizes the PID parameters by simulating a population of candidate solutions (particles) that then seeks the best solutions by exploring the parameter space. The position of each particle denotes potential solution and the particle move based on its own experience and of its neighboring particles. As a result this results in efficient convergence towards optimal PID parameters. Furthermore, response time, overshoot,

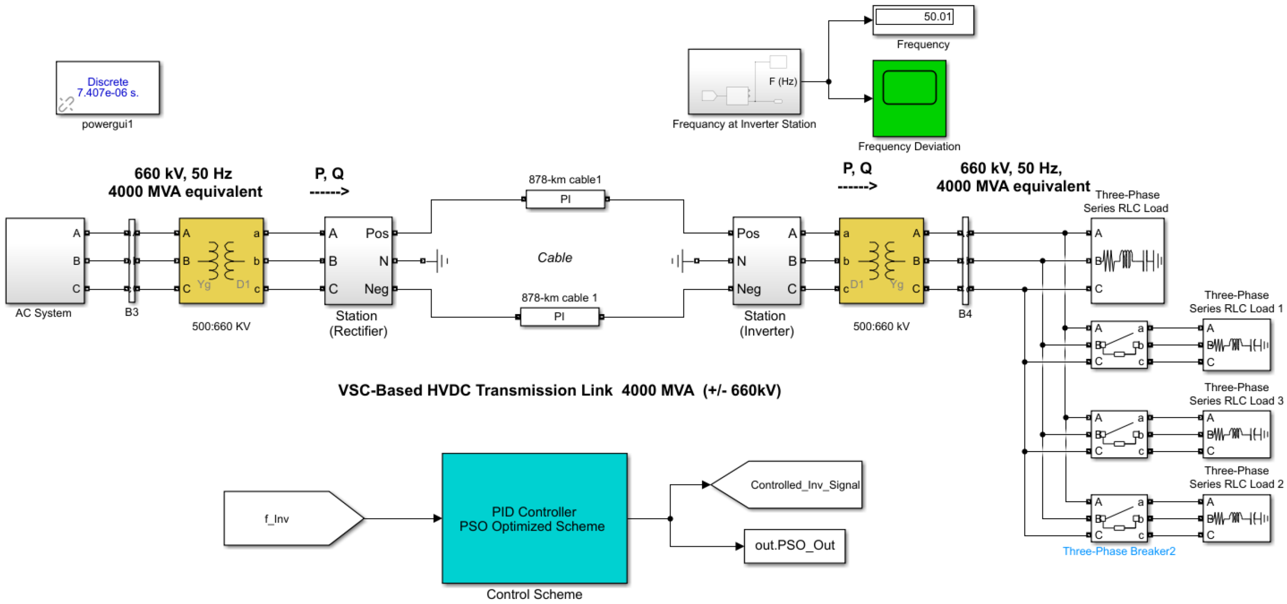


FIGURE 21 | PID-PSO based HVDC transmission system.

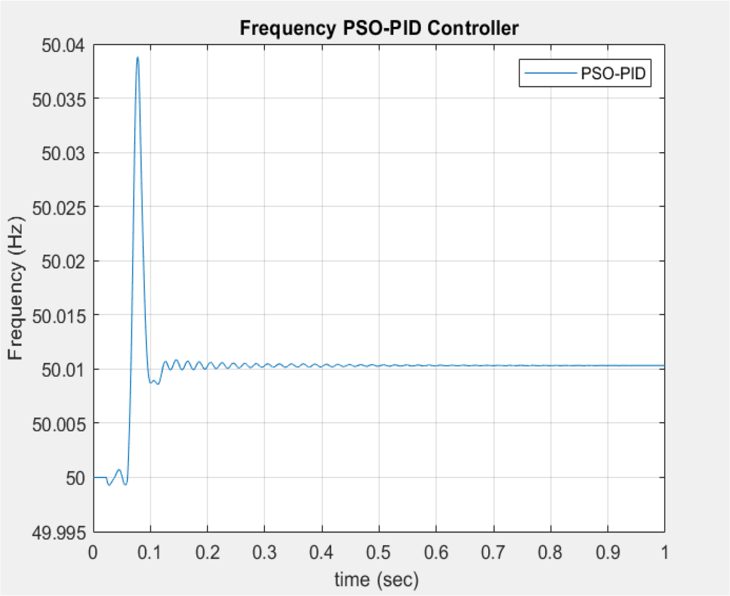


FIGURE 22 | Results with PID-PSO controller.

and settling time have been shown for PSO tuned PID controllers to outperform traditionally tuned controllers. PSO-PID controller proves to be efficient to compensate for the load and systems' parameters variations, and so it can be used in real time applications in dynamic environments. The model can easily be adapted to different power system configurations, and is equally applicable to single area or multi area systems. PSO converges faster than other optimization methods, which could be necessary for timely correction of frequency in real time.

5 | Comparative Analysis

Simulations results indicated that all control options were effective in controlling frequency. However, comparative research indicated that the ANN based control strategy outperformed the competing strategies as indicated by Figure 23. The ANN was able to produce consistently precise frequency control results because of the fact that it can learn from historical data as well as its ability to adjust its control response dynamically with inputs of real time frequency and rate of change of frequency. It is observed that under varying load conditions the ANN approach always kept the frequency within a narrow region around the desired reference frequency with small deviations except at one instant and close time response. The ANFIS controller also showed impressive results, adjusting the firing angle. Control responses were shown by the ANFIS controller to be efficient and following closely. On the other hand, PID-PSO optimization exhibited adaptive nature accompanied by moderate deviations. Although PID-PSO was

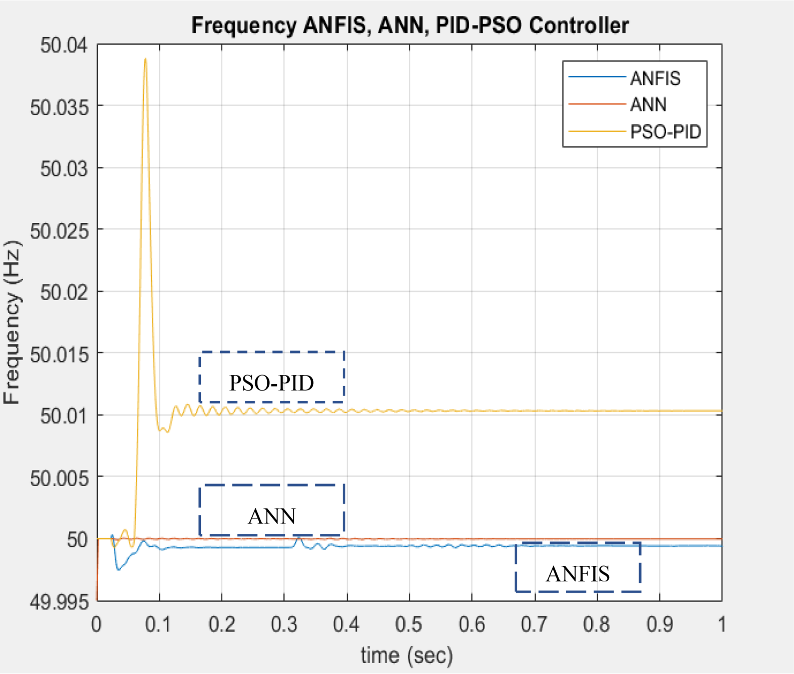


FIGURE 23 | Comparative results analysis of ANN, ANFIS, and PID-PSO controllers.

TABLE 5 | Comparative analysis of the controllers.

Controller	Controller response	Response time (min)	Operation
ANFIS controller	Stabilize frequency immediately after disturbances	15	Automatic
ANN controller	Stabilize frequency immediately after disturbances	15	Automatic
PID-PSO controller	Stabilize frequency immediately after disturbances	15	Automatic

effective, its response to dynamic load variations was slower than that of the other approaches.

Despite every controller demonstrating the ability to control frequency and help stabilize the grid, one stands out. This lack of a controller is quite telling about the importance of these techniques for addressing frequency instability problems. In comparison with the other controllers, the ANN-based technique possessed a unique versatility and could rapidly accommodate changes in the dynamic load, while ensuring stable frequency levels. Meanwhile, ANFIS stayed close behind profiting from its efficient firing angle adjustments. In this visual conclusion, no controller serves to call out just how important these clever control techniques are in order to sustain reliable energy transfer. The results show how these controllers can radically alter the way frequencies are managed, and represent a clear path to a more stable energy future. The results of such comparative research provide us with insights into the possibility of using these technologies for providing grid stability and smooth HVDC energy transmission as the energy system evolves.

The proposed methods for frequency control in power system are much better than the other conventional methods as shown in Table 4 alongside, these all controllers are used to stabilize the frequency immediately after the disturbances occur in the power system (Table 5).

Non-linear loads significantly impact the frequency and overall performance of electrical power systems as shown in Figure 24. These loads, which include devices such as variable frequency drives, uninterruptible power supplies (UPS), and electronic ballasts, draw current in a non-sinusoidal manner, leading to various challenges primarily associated with harmonic distortion [43]. Non-linear loads generate harmonic currents, which are currents at frequencies that are integral multiples of the fundamental frequency. This generation occurs because these loads do not consume current in a linear fashion relative to the voltage applied. The harmonic currents interact with the supply system impedance, resulting in distortions in both voltage and current waveforms. This distortion can lead to increased losses in the system, overheating of equipment, and malfunctioning of protective devices. The level of harmonic distortion is often quantified using Total Harmonic Distortion (THD), which measures the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. High THD values can indicate poor power quality and can lead to operational issues in electrical

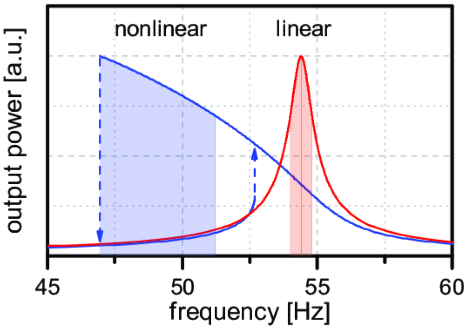


FIGURE 24 | Effects of linear and non-linear loads on frequency of power system.

systems. Non-linear loads exhibit frequency-dependent behavior that affects their impedance characteristics. This means that as the frequency of the system changes, the impedance presented by these loads can also change, potentially destabilizing the power system. The introduction of harmonics can cause fluctuations in system frequency, especially under varying load conditions. This can lead to resonance phenomena where certain frequencies may amplify due to interactions between different components of the power system.

Frequency stability analysis is dependent on inertial and damping parameters. The equivalent inertia indicates the system's ability to oppose frequency variation, while the damping factor characterizes the behavior of the load power to the frequency variation [44]. Increased renewable penetration will decrease the synchronous generation leading to insufficient inertia thus rendering the system prone to frequency deviations. Frequency stability can be affected by not only the proportional degrees of freedom in the transmit and receive channels, but also by communication delays in control systems. With modern power systems becoming increasingly decentralized and data exchange among components of the power system being done over networks, neglecting such delays in stability analyses is becoming less appropriate. It has been demonstrated that lower bound, as well as non-zero time delays affect the LFC performance, which makes robust control methods necessary to be working in the presence of such delays. As current research shows, simulation models have been used to analyze frequency stability under different scenarios with different levels of renewable integration and different system parameters, in our case much of the validation was done using MATLAB/Simulink in order to develop methodologies that evaluate frequency stability with respect to communication delay and other dynamic factors.

The performance of the ANFIS controller for frequency control in power systems have some of the advantage and disadvantage of the controller. From the positive side, ANFIS brings in the learning characteristics to neural networks and the reasoning characteristics to fuzzy logic, aptitude at tackling operational conditions and disturbances, and as a consequence generally outperforms a standard controller, for instance, a Proportional Integral (PI) controller [45]. Because of this adaptability, ANFIS can reduce the frequency deviation much better with less overshoot and a better settling time. Moreover, it has the ability to adapt the membership functions by incorporating the training data, and hence can deal more robustly with uncertainties including from renewables. Yet, ANFIS is difficult to implement. Specifically, it becomes computationally intensive and time consuming to tune ANFIS parameters using the large amount of training data that results in an optimal performance of the method [46]. Additionally, the controller can be sensitive to initial conditions and to the quality of the input data, and may operate poorly if these are not handled properly. Last but not least, fuzzy logic provides some interpretability, with the caveat that integrating with neural networks only adds to this lack of transparency and hinders users from being able to understand how decision making occurs. ANFIS is, in general, a powerful tool to control the load frequency and, at the same time, its complexity and requirements for the ANFIS training are such that their practical applications need to be well thought out [47].

The power system frequency control is applied to the controller, which possesses several advantages and drawbacks. It has one of the primary advantages, which is the ability to learn that can be used, for example, to adapt to a dynamic, or altered, or disturbance in power system, which makes it overall perform better then more traditional controllers. Modeling complex nonlinear relationships by ANN and minimizing frequency deviations and reducing settling times can improve system stability [48]. Also, its flexibility allows it to be used in a wide range of configurations including multi area power systems. The major draw backs, however, is the training of an ANN is demanding a large amount of high quality data, which can be difficult to come by, and the training itself can be quite computationally demanding. In addition to this, the ANN decision making is not interpretable, and poses problems for operators who require to reason about the underlying reason for control actions [49]. Lastly, if the training data does not reflect and encompass all possible operating conditions, ANNs can struggle with generalization and hence suboptimal performance could occurs in unanticipated situations. ANN controllers are able to provide advanced capabilities for frequency control in power systems, but they go at the cost of complexity and data dependency [50].

Frequency control of power systems using PID-PSO controller provides significant advantages and disadvantages. Another main benefit is that, PID controller parameters optimization yields better system performance (smaller overshoot and shorter settling time) than traditional methods such as Ziegler–Nichols [51]. The PSO algorithm is particularly appealing because of its simplicity and efficiency in finding optimal solutions, few parameters need to be tuned for convergence testing and the PSO is good to handle those complex and nonlinear problems. Additionally, PID control together with PSO improves the robust characteristics of frequency control within interconnected power systems through the capacity to cope with load disturbance more efficiently [52]. However, PID-PSO has some serious disadvantages: the performance of such controller significantly depends on the initial parameter settings and on the chosen objective function to be optimized. Furthermore, although PSO works well for tuning, it may be computationally burdensome for large scale systems and its performance is susceptible to changes in the dynamics of the system [53]. Additionally, the complexity of the optimization process can result in control strategy, which is hard to understand, thereby compromising their interpretability and making it difficult for operators to comprehend underlying decision making framework. Also, the PID-PSO controller is a robust frequency regulation method for power systems and yet the considerations of its limitations are important for the effective implementation [54–60].

6 | Conclusion

The growing energy demand to meet growing power generation will disturb the frequency of power transmission network hence frequency control solutions have been proposed in this study. This paper investigated the area of intelligent frequency regulation in the HVDC transmission system in order to improve the grid stability and ensure constant power supply. In this study, a number of control methods are thoroughly examined to find the most efficient way to preserve stable frequency level under dynamic load conditions, including Artificial Neural Networks (ANN), Adaptive Neuro Fuzzy Inference Systems (ANFIS), and Particle Swarm Optimization (PSO) is employed to optimize Proportional Integral Derivative (PID) controller parameters for frequency control in HVDC transmission systems. PSO imitates particle movement in search space to optimize in an iterative nature the parametric values of Kp, Ki, and Kd (PID controller). Various control schemes were assessed using MATLAB model to accurately model the HVDC transmission system. Extensive AC supply, converter stations, HVDC transmission line, inverter station and three phase AC load were integrated in the model. Striking this balance, this enabled the study analyze the effectiveness of each control strategy, under relatively realistic complexities that the real-world could present. Simulation results showed that all the control techniques examined have the capacity of preserving frequency stability to some extent. Although each strategy had its own unique advantages, a comparison demonstrated that ANN based control strategy achieves better performance while correctly monitoring 50 Hz frequency. Furthermore, due to its rapid response to frequency changes and the rate of change of frequency inputs as well as its ability to learn from historic data, the ANN minimized frequency deviations and recovered the stability very closely and effectively. ANFIS controller was closely studied for its efficiency in adjusting firing angles to maintain optimum frequency levels. In contrast, the load scenarios of the PSO optimization showed adaptability. As energy systems continue to change, the results of this study make important contributions to the field of frequency regulation in HVDC transmission networks. The potential use of intelligent control strategies, specifically the ANN based strategy, has the potential to totally change the stability of the power system. These control approaches lead to higher efficiency of HVDC transmission and provide a more flexible and accurate mechanism for frequency sustaining, and, hence, support better dependability and resilience of power grids. Investigating intelligent frequency control solutions in HVDC networks however has provided insightful information. In particular, this paper highlights how important it is to exploit technical breakthroughs in terms of ANN based control techniques to tackle the dynamic aspects arising from the modern energy demands. Implementing intelligent control techniques guarantees continuous energy flow and leads to sustainable growth for coming generations and a better, more stable power system in the future.

Future work consists on the invention of other efficient techniques for handling and maintaining the frequency of load in the connected HVDC transmission system. Efficient techniques should involve the power electronics component for the effective operation.

Author Contributions

Saleem: conceptualization, investigation, writing – original draft, writing – review and editing, visualization, validation, methodology. **Muhammad Amir Raza:** writing – original draft, writing – review and editing, methodology, formal analysis, project administration, supervision. **Syed Waqar Umer:** conceptualization, validation, methodology, formal analysis, data curation. **Muhammad Faheem:** supervision, resources, project administration, formal analysis, software, conceptualization. **Touqeer Ahmed Jumani:** supervision, resources, project administration, visualization, investigation. **Muhammad Yameen:** investigation, funding acquisition, methodology, validation, formal analysis, project administration.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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