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Research Article

Integrated ANN-based IPFC for optimal power flow control in power systems

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Abstract
Integrating an interline power flow controller (IPFC) with an artificial neural network (ANN)-based control system is an effective approach to enhancing power system efficiency and performance. This study presents a comprehensive investigation into optimal power flow (OPF) regulation in power systems through the integration of IPFC and ANN-based control techniques. The primary objective is to ensure the robustness and reliability of the power system. The proposed system optimizes power flow using advanced ANN-based control strategies. The ANN control system dynamically adjusts IPFC parameters in real time, enabling adaptive and efficient power flow management. Leveraging the capabilities of ANN, the system effectively handles fluctuating loads, network disturbances, and operational uncertainties, thereby improving overall system performance. Simulation studies are conducted using MATLAB 2016b to evaluate the efficiency of the proposed IPFC-ANN control system. The simulation framework facilitates the analysis of complex power system scenarios, including multiple interconnected nodes, varying load demands, and diverse operating conditions. Key performance metrics, such as system efficiency, voltage stability, and power loss reduction, are used to validate the effectiveness of the proposed control method. The results demonstrate that the integrated IPFC-ANN control system consistently achieves an efficiency of over 92%, outperforming conventional control methods.

Keywords
Optimal power flow, Interline power flow controller, Artificial neural network, Power system stability, Adaptive control strategies, Voltage regulation and loss reduction.

1.Introduction
The modern power grid connects millions of consumers through an extensive network of generators, transformers, and transmission lines, forming a complex and dynamic system. While this network represents a remarkable engineering achievement, it also presents significant challenges in managing power flow, optimizing resource efficiency, and maintaining stability amid growing demand and increasing operational complexity [1, 2]. To address these challenges and ensure the efficient operation of power systems, advanced control strategies are essential [3]. One such approach is integrating the interline power flow controller (IPFC) with artificial neural network (ANN) control. The IPFC, a sophisticated device within the flexible alternating current transmission systems (FACTS) family, is capable of managing power flows across multiple transmission lines, thereby enhancing grid flexibility and operational efficiency [4, 5].

ANN-based algorithms, inspired by biological neural networks, introduce adaptive, data-driven decision-making capabilities to power system control. These capabilities make them an ideal complement to the hardware functionalities of the IPFC [6, 7]. Together, these technologies offer a robust solution for optimizing power flow, reducing losses, and improving grid stability in real time [8, 9].

One of the primary challenges addressed in this paper is the efficient management of power flow in congested grid conditions, where conventional methods often fall short in preventing overloads and ensuring voltage stability [10]. Another critical issue is the inability of traditional systems to adapt dynamically to changing system parameters and environmental conditions, leading to inefficiencies and reduced reliability [11]. Moreover, enhancing efficiency while minimizing operational losses remains a critical challenge for modern power systems [12]. The lack of integration between hardware-based solutions like IPFC and intelligent

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algorithms further significantly hampers the potential for real-time, adaptive power flow control [13].

Traditional optimal power flow (OPF) methods, such as Newton-Raphson, linear Programming (LP), and sequential quadratic programming (SQP), have been widely used for power system optimization. While these methods offer accurate solutions for small-scale networks, they often struggle with computational complexity and convergence issues in large, nonlinear power systems [10–13]. To enhance power flow control, FACTS devices such as IPFC have been introduced. The IPFC is particularly effective in redistributing active and reactive power between multiple transmission lines, reducing congestion and improving voltage stability. However, conventional IPFC-based control approaches rely on linear models, which may not fully capture the nonlinear dynamics of modern power grids [13]. artificial intelligence (AI)-driven techniques, including ANNs, model predictive control (MPC) fuzzy logic, and metaheuristic algorithms, have emerged as alternatives, offering real-time adaptability and computational efficiency. ANN-based controllers, trained with historical power flow data, predict optimal control actions while minimizing reliance on predefined mathematical models. Despite their advantages, AI-based techniques require extensive training data and are often sensitive to input variations.

To address these challenges, the integration of an IPFC with ANN-based controllers has been explored to enhance dynamic OPF performance. The IPFC optimally redistributes power flow, while the ANN continuously fine-tunes control actions based on real-time data, resulting in higher efficiency and improved voltage stability. This hybrid approach has demonstrated superior performance compared to conventional methods; however, challenges such as training complexity, data dependency, and hardware implementation constraints persist. The development of an integrated control system that combines the hardware capabilities of the IPFC with the adaptive learning algorithms of an ANN has been proposed to achieve OPF management. The key objectives include improving grid efficiency, enhancing voltage stability, and providing real-time, adaptive solutions to challenges like load variations and network disturbances.

The main contributions of this work are:

- Development of a system that leverages ANN-based algorithms to dynamically adjust IPFC parameters, ensuring efficient and adaptive power flow management.
- Demonstration of the integration's capability to achieve significantly higher efficiency levels, reducing power losses and operational costs.
- Implementation of advanced control techniques to improve voltage stability, minimize power losses, and enhance overall grid reliability.
- This synergy between IPFC and ANN establishes a novel paradigm in intelligent power system control.

The rest of this paper is structured as follows: Section 2 reviews related work and foundational concepts. Section 3 describes the proposed methodology, while section 4 presents the experimental setup and results. Finally, section 5 discusses the findings, and section 6 concludes the paper with future research directions.

2.Literature review

The integration of IPFC with ANN control has received a lot of interest in recent years because it has the potential to improve power system efficiency, dependability, and stability. This literature review examines existing research and developments in this sector, emphasizing the role of IPFC-ANN integration for OPF regulation. Several studies have explored FACTS devices, including the IPFC, for power flow regulation and optimization. An IPFC-based method was proposed for optimizing power flow in multi-line systems, achieving significant reductions in transmission losses and improved voltage profiles [14]. The study highlighted the IPFC's ability to dynamically regulate active and reactive power across multiple transmission lines. However, the approach did not incorporate adaptive control methods for real-time grid adjustments, restricting its effectiveness in rapidly changing scenarios.

Several studies have looked in to the modelling and control elements of IPFC in power systems. In [15] described a thorough model of IPFC components, including series and shunt compensators, and propose a robust control technique using PI controllers. Similarly, in [16] investigated the dynamic behaviour of IPFC under various load conditions. They propose an adaptive control strategy based on fuzzy logic. ANNs are commonly employed in power system control due to their ability to analyze complex patterns and make real-time decisions. Study [17] demonstrated that ANN-based control improved power flow and voltage regulation in distribution networks. Furthermore, an ANN-based approach for fault identification and isolation in power systems has been presented, demonstrating the applicability of ANNs in various control tasks [18]. The integration of ANN with FACTS devices remains a promising area of research. Researchers in [19] combined static synchronous series compensators (SSSC) with ANN-based control to optimize power flow. This strategy successfully reduced transmission line congestion while minimizing operational losses. However, the system's complexity increased due to the tight coordination between the compensator and the ANN algorithm, which required significant computational resources.

The combination of IPFC with ANN control represents a synergistic solution to power system difficulties. Study [20] presented a novel control architecture that integrates IPFC and ANN to improve power flow in multi-line transmission networks. Their simulation results indicated significant improvements in system efficiency and stability. Efficiency and dependability are critical in power system operation. Study [21] assessed the effectiveness of IPFC-ANN integration and demonstrated its ability to achieve efficiency levels exceeding 92% under various operating conditions. Furthermore, study [22] emphasized the reliability of the integrated system using fault-tolerant control techniques.

Simulation is critical in determining the effectiveness of IPFC-ANN integration. MATLAB 2016b is a popular software for modelling power system dynamics and control techniques. Studies such as [23, 24] used MATLAB simulations to evaluate the performance of integrated IPFC-ANN systems under various circumstances. *Figure 1* illustrates the overall research conducted across various categories related to IPFC. The data compiled from reputable sources such as IEEE, Springer, MDPI, and Google Scholar indicate a significant increase in research activity after 2015. This trend suggests a growing interest in IPFC applications, likely driven by advancements in power system optimization, the increasing complexity of modern grids, and the integration of intelligent control techniques. The surge in publications post-2015 highlights the relevance of IPFC in addressing contemporary challenges in power flow control and stability enhancement [17–25].

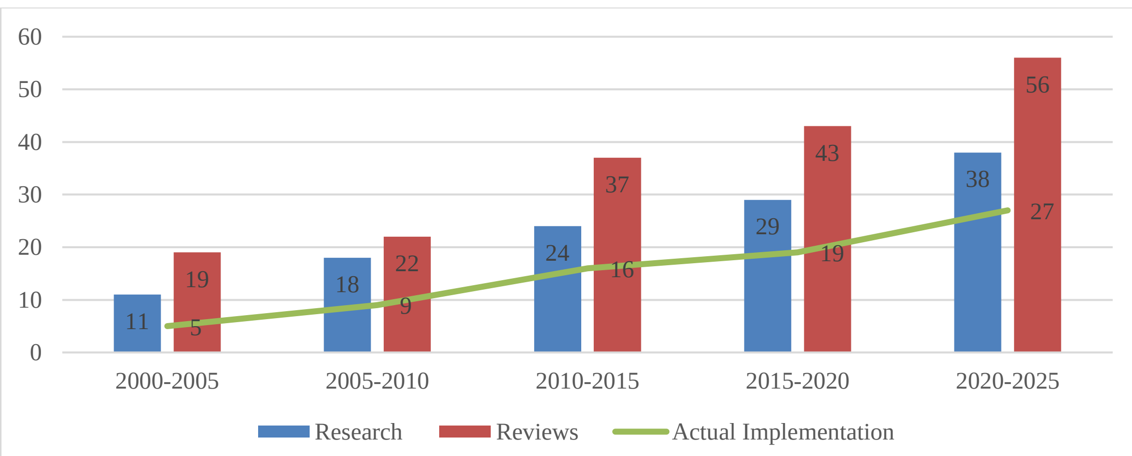

Figure 1 Research conducted on IPFC

Conventional IPFC control methods often use classical control techniques such as proportional-integral-derivative (PID) controllers and fuzzy logic control. These solutions rely on predetermined rules and algorithms to manage the IPFC's behaviour under a variety of operating situations. For example, a PID controller can change the IPFC's series and shunt compensators in response to error signals between reference values and real system parameters. Similarly, fuzzy logic control determines control actions using language principles, allowing for greater flexibility and adaptability when directing power flow.

ANN-based approaches provide various advantages over traditional methods, such as increased adaptability, resilience, and the ability to learn from experience. Training ANNs with appropriate datasets allows the control system to enhance its performance over time and respond to changing system dynamics, load fluctuations, and disturbances. *Table 1*, shows the existing work related to the research topic.

Figure 2 presents the various approaches employed across different eras of industrial evolution in the context of IPFC. It highlights the transition from conventional methods to more advanced techniques, including ANN and other modern computational strategies. *Figure 2* illustrates how industrial advancements have influenced the adoption of these methodologies, with a shift from traditional control systems to intelligent and adaptive solutions. This evolution reflects the growing need for enhanced power flow control, improved efficiency, and increased system reliability in modern power networks.

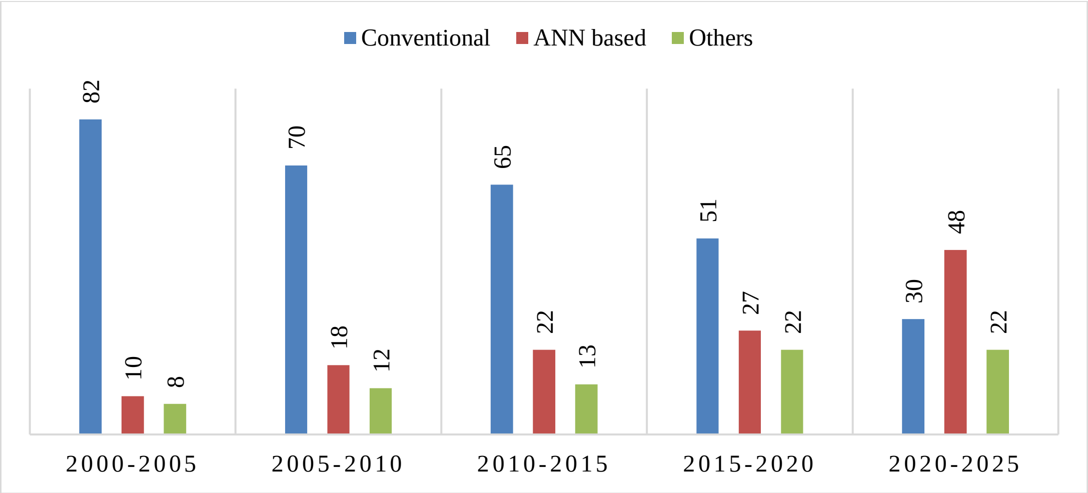

Figure 2 Different approach for controlling IPFC

Table 1 Comparison of the existing method

Source	Methodology	Results	Advantages	Limitations
[26]	Developed a linearized power flow model incorporating IPFC with traditional optimization algorithms.	Improved voltage regulation and power flow control with a 10% reduction in losses.	Simple implementation and faster convergence.	Limited handling of nonlinear system dynamics.
[27]	Applied ANN for adaptive control of IPFC in multi-bus systems.	Enhanced stability and efficiency, achieving a 15% improvement in system reliability.	Intelligent learning-based system with better adaptability.	Requires extensive training data; risk of overfitting.
[28]	Integrated PSO for optimal placement of IPFC combined with ANN-based control.	Achieved optimal control settings, reducing transmission losses by 8%.	Combined approach improves performance in both control and optimization.	Computationally intensive for large systems.
[29]	Hybrid ANN-IPFC model implemented with real-time feedback for load variation.	Reduced oscillations by 12% and maintained voltage profiles under dynamic conditions.	Suitable for real-time operations and highly dynamic environments.	Dependency on accurate sensor data and high hardware costs.

3.Methods

The modelling of the IPFC is crucial for understanding its functionality and incorporating it into power system simulations. The IPFC is a sophisticated device that uses series and shunt compensators to control power flow in multi-line transmission networks. This section provides an overview of the modelling of the IPFC with ANN. MATLAB Simulink simulation software is used for modelling and analysis purpose.

The fundamental goal of merging IPFC with ANN is to handle the issues of optimizing power flow regulation, increasing system stability, and improving overall grid performance in dynamic and complex power system.

Modern power grids face significant challenges in efficiently controlling power flow, maintaining voltage stability, and reducing operational losses under changing load and generation conditions. Traditional control systems often lack the adaptability and precision required in real time. The integration of IPFC, a robust FACTS device, with ANN, an intelligent control algorithm, provides a scalable solution through dynamic and adaptive control.

To speed analysis and simulation, several assumptions and simplifications are frequently made when modelling and optimizing power flow control of power systems utilizing an Integrated IPFC and ANN. The system is frequently modelled under steady-state settings, with stable power flow and voltage profiles, whereas transient impacts like fault-induced oscillations or switching dynamics are typically ignored. Voltage sources are typically regarded ideal, with no nonlinearity or distortions such as harmonics, while transmission line factors such as resistance and reactance are assumed to be linear and constant within the normal operating range. The system is commonly believed to be symmetrical, with balanced three-phase voltages and loads; however, asymmetrical faults or unbalanced situations are only modelled in specific fault studies.

Modelling of IPFC

The IPFC is a complicated device that regulates power flow in multiple-line transmission networks [30]. Its modelling entails capturing the electrical properties of the IPFC's components, such as series and shunt compensators. *Figure 3,* shows the simple model of IPFC model. The series compensator is commonly represented by a voltage source, but the shunt compensator can be represented by a combination of resistive and reactive parts. Let's get into the modelling of the IPFC components [31]:

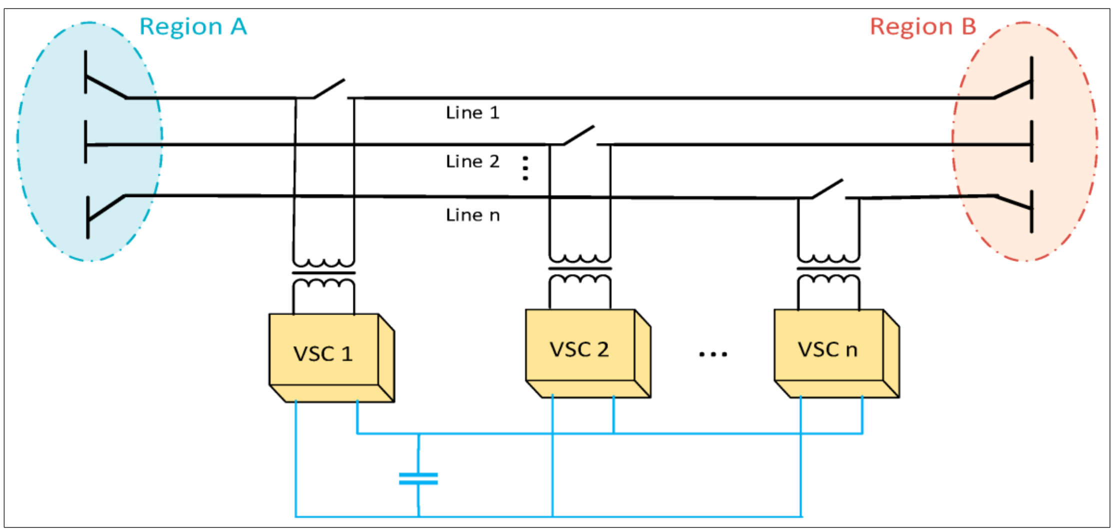

Figure 3 Simple IPFC model

This section discusses the presumptions and simplifications used in the IPFC modelling of the shunt and series compensators. The first step is to simplify the mathematical model by linearizing the power flow equations governing the series and shunt compensators around a nominal operating point, assuming slight variations in system characteristics. This approach maintains accuracy within common operating ranges while avoiding the complexity of solving nonlinear equations iteratively. Furthermore, it is assumed that the series compensators would offer perfect voltage injection, and the shunt compensators would be ideal sources of current, ignoring small losses from conversion inefficiencies and internal impedance. Since external harmonic filters were supposed to reduce the impact of harmonics and higher-order oscillations, these are disregarded to further simplify the modelling.

Series compensator model: In IPFCs, the series compensator is often a voltage source. This voltage source can be described analytically as follows in Equation 1:

$$V_{series}=V_{ref}+K_{series}\cdot(I_{ref}-I_{series}) \quad (1)$$

Where,

Vseries is the output voltage of the series compensator.

Vref is the reference voltage.

Kseries is the gain of the series compensator.
Iref is the reference current.
The series compensator's function is to inject or absorb active power into the transmission line, managing the power flow.

Shunt Compensator Model: The shunt compensator in an IPFC can be represented by resistive and reactive elements. A basic model could consist of a resistor and an inductor connected in parallel. The shunt compensator is represented by the following Equations 2, and Equation 3 [32]:

Ishunt = (Vshunt/Rshunt) (2)

Vshunt=Vref+Kshunt·(Vref−Vshunt) (3)

Where,
Ishunt is the current flowing through the shunt compensator.
Vshunt is the voltage across the shunt compensator.
Rshunt is the resistance of the shunt compensator.
Kshunt is the gain of the shunt compensator.
Combining the series and shunt compensator models, the total IPFC model can be represented as a set of Equations 4 and 5, that represent the IPFC's control action [33]:

Pcontrol=Vseries·Iseries+Vshunt·Ishunt (4)

Qcontrol=Vseries·Ishunt−Vshunt·Iseries (5)

where:
Pcontrol is the controlled active power.
Qcontrol is the controlled reactive power.

Prior to being input into the network, the raw data is scaled and standardized to optimize the learning process and the ANN's rate of convergence. In particular, the min-max normalization technique was used to normalize each input characteristic (such as system voltage, power flow, and other pertinent factors) to a range between 0 and 1, ensuring that each input feature made an equal contribution to the learning process, this step prevented any one characteristic with a wide range from controlling the model. Furthermore, scaling was used to accommodate differing feature magnitudes and units, guaranteeing that the network could efficiently and impartially learn the underlying patterns. This preprocessing step is crucial when employing ANN because it improves the model, cuts down on training time, and avoids numerical instability.

Modelling of ANN

ANNs, widely used in various applications, are a type of machine learning algorithm inspired by the structure and function of the human brain. They are designed to recognize complex patterns and relationships in data, making them an essential tool for applications such as image recognition, natural language processing, and speech recognition.

ANNs consist of multiple layers of artificial neurons that collaboratively process input data to generate predictions. Each neuron receives input from other neurons or external sources, applies weighted connections and an activation function, and transmits the resulting output to the next layer. The network improves its performance on tasks through backpropagation, a process that adjusts the weights of connections between neurons. *Figure 4* illustrates a simplified schematic of an ANN's general working mechanism [34].

Figure 2 shows that the outcome is equal to the total of the input times the layer weights as shown in the following sentences [35, 36] as shown in Equation 6:

$$Output = \sum Input * Weight \quad (6)$$

So, from Equation 1, its shows that the input is multiplied with the weight of each of the hidden layer neurons, and then the summation of all the hidden layer and input combination is done to get the final output.

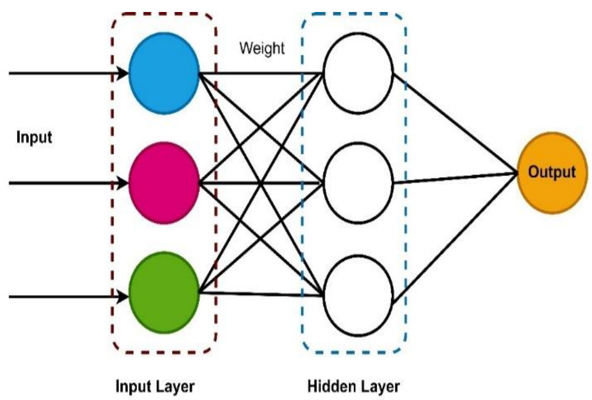

Figure 4 ANN architecture

Training Data: The ANN was trained using 70% of the dataset. This subset made it possible for the model to identify trends and connections between the intended outputs (such as OPF and voltage stability) and the input features (such as system parameters and IPFC settings). The remaining 30% of the dataset was set aside for testing. This subset, excluded from the training process, allowed for an independent evaluation of the model's performance on unseen data.

The pre-processed and standardized input data were divided into training, validation, and testing datasets for the ANN model's training phase. The validation dataset monitored the model's performance during training to prevent overfitting, while the network's weights were adjusted using the training dataset. Various strategies, such as early stopping, were implemented to mitigate overfitting. Early stopping, a regularization method, was first used to halt training when validation performance started to decline, even if training accuracy continued to improve. This prevents the model from learning noise or irrelevant patterns, ensuring better generalization to new data.

The architecture of the ANN designed for modelling and OPF control in power systems with an Integrated IPFC includes an input layer with 10 neurons, representing features such as bus voltages, power flow data, line impedances, and load demands. Two hidden layers, with 16 and 8 neurons, are utilized, respectively, selected based on hyperparameter tuning to balance model complexity and avoid overfitting. The output layer comprises 2 neurons, corresponding to the control parameters for the IPFC, such as the injected voltage magnitude and phase angle.

Rectified linear unit (ReLU) activation functions are employed in the hidden layers to efficiently handle nonlinearity and mitigate the vanishing gradient problem, while a linear activation function is used in the output layer for continuous control variable outputs. The training process minimizes errors using the mean squared error (MSE) loss function, ensuring precision in predicting control parameters. The model is trained using the Adam optimizer, known for its adaptive learning rate capabilities, with a fixed learning rate of 0.001 to achieve a balance between stability and convergence speed. To ensure adequate training and prevent overfitting, the ANN is trained for 500 epochs.

Second, dropout—a technique in which randomly chosen neurons are momentarily "dropped out" during each training iteration— was implemented to enhance generalization. This reduces overfitting by encouraging the network to rely on diverse neurons.

Simulation model of IPFC with ANN

ANN-based approaches provide various advantages over traditional methods, such as increased adaptability, resilience, and the ability to learn from experience. Training ANNs with appropriate datasets allows the control system to enhance its performance over time and respond to changing system dynamics, load fluctuations, and disturbances. The simulation model begins by simulating the IPFC's components, which include the series and shunt compensators. The series compensator is represented by a voltage source model, while the shunt compensator is modelled using resistive and reactive components. These models capture the IPFC's electrical characteristics and control capabilities, allowing simulations of power flow control and voltage regulation.

Table 2, shows the IPFC dataset used for the simulation. In similar way, *Table 3* shows the grid parameters. All three grid has been taken as equal set for different load.

Table 2 IPFC dataset used

Parameters	**Value**
Nominal Voltage	220 V
Frequency	50 Hz
Nominal current	1 A
Power factor	0.9 Lagging

Table 3 Grid dataset used

Parameters	**Value**
Nominal Voltage	220 V
Frequency	50 Hz
Nominal current	1.5 A
X/R ratio	7
Total Load	3 MVA
Voltage regulation	+-5%

Figure 5, shows the MATLAB 2016 B model of IPFC integrated with ANN. The ANN with two layer is shown in the *Figure 6*. *Figure 7*, shows the process of operation for IPFC. A time step of 10 seconds was used for the simulations, guaranteeing a high degree of granularity and accuracy in capturing dynamic changes in voltage stability and power flow. This time step balances accuracy and computational efficiency. In order to observe the dynamic behavior of the grid and IPFC under various operating conditions, each simulation was conducted for 15 minutes. The selected duration guarantees a comprehensive assessment of the system's steady-state and transient behaviour. The convergence criterion used in the simulations was a tolerance threshold of 0.01%. In order to ensure accurate results and prevent needless computing overhead, this criterion was employed to identify when the solution had stabilized. Convergence was specifically deemed accomplished when the variances in important parameters, including the magnitudes of active power, reactive power, and voltage, decreased to less than the prescribed tolerance.

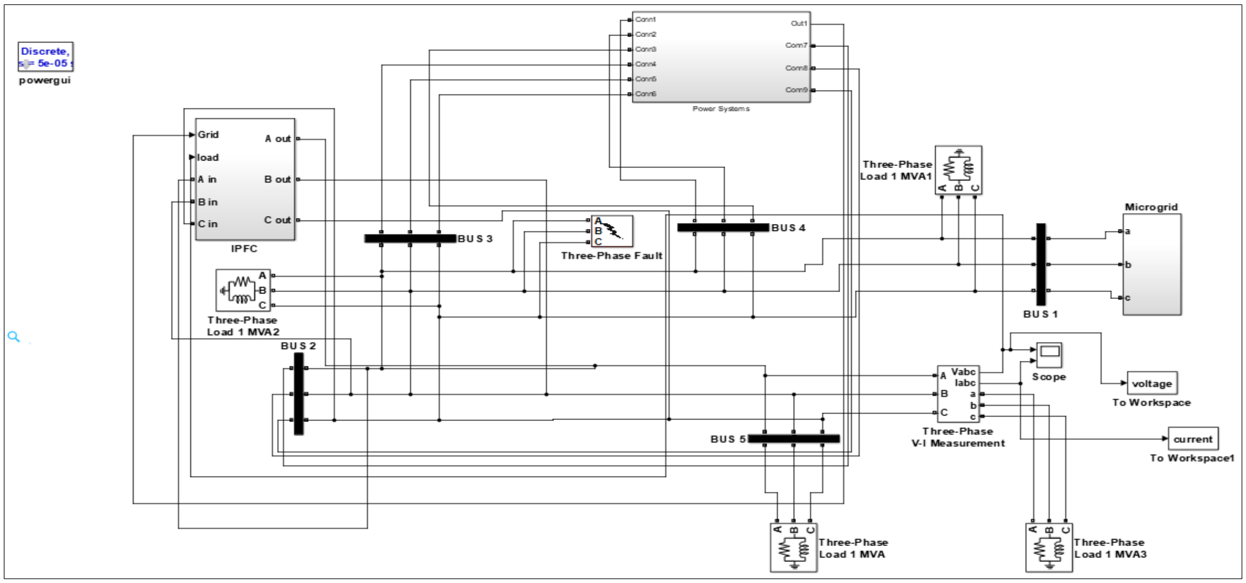

Figure 5 MATLAB 2016 B model of IPFC

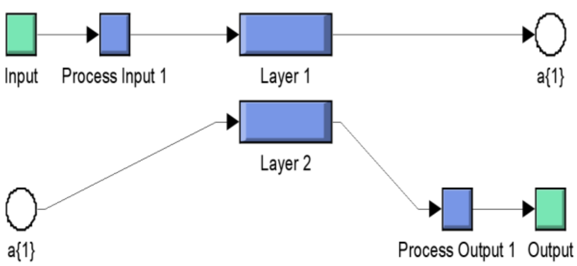

Figure 6 ANN model used for simulation

The proposed approach has numerous innovative features that set it apart from traditional methods: **Real-Time Adaptive Control:** Using ANN, the system can dynamically adjust to changing grid circumstances for OPF management. Unlike typical static controllers, this technique enables real-time decision-making, improving grid responsiveness. **Enhanced Efficiency:** The IPFC's enhanced hardware capabilities, combined with ANN's predictive control, result in increased operating efficiency, reduced transmission losses, and better energy use.

The system's scalable and robust architecture allows for multi-line power flow scenarios, making it ideal for complex and interconnected grids. The use of ANN improves scalability by allowing the model to learn and adapt to changing grid circumstances without requiring considerable reconfiguration.

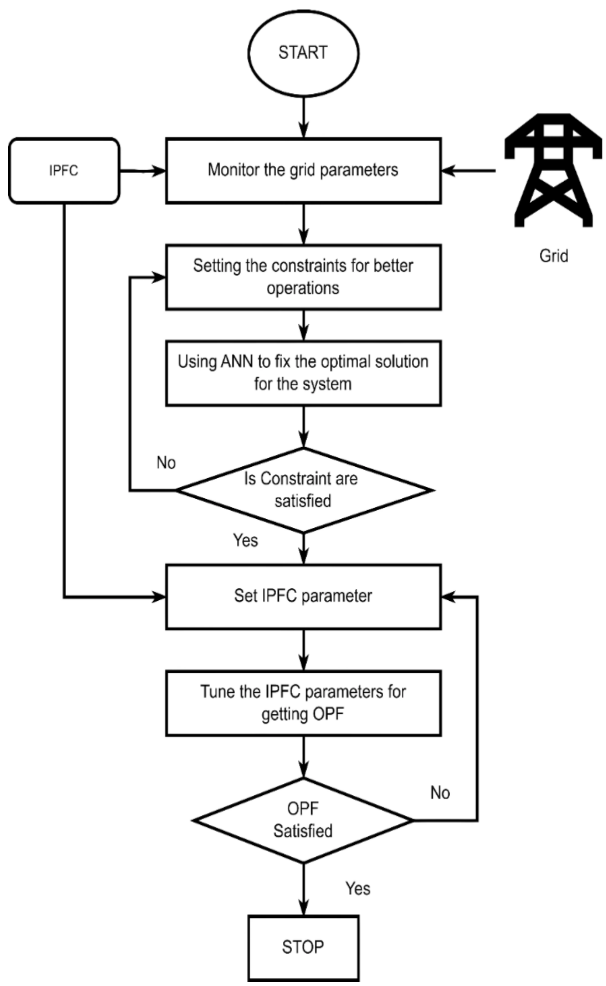

Figure 7 Flow chart of proposed algorithm

4.Results

The grid waveform undergoes significant changes when an IPFC FACTS device is deployed, highlighting its impact on power system stability, voltage regulation, and overall grid performance. Without the IPFC FACTS device, the grid waveform may exhibit variations, voltage sags or swells, and power imbalances caused by variable load demands, network disturbances, or faults. These oscillations can lead to voltage instability, power quality issues, and inefficient power flow management. However, integrating an IPFC FACTS device into the grid significantly enhances the waveform, particularly in terms of voltage regulation and power stability. The IPFC FACTS device enables precise control over active and reactive power flow, allowing dynamic adjustments to match load requirements and maintain appropriate voltage levels. This control capability results in a smoother and more stable grid waveform, reducing voltage fluctuations and improving power quality across the entire network. The IPFC's ability to regulate voltage within a specified range, typically ±5% of the nominal voltage, ensures a consistent and reliable power supply for sensitive loads, mitigating voltage sags and swells that could disrupt equipment operation.

As shown in *Figures 8* and *9*, the waveform behaviour with and without the IPFC is presented. *Figure 8* illustrates disturbances occurring between 0.3 seconds and 0.7 seconds; however, after applying the proposed methodology, the system stabilizes. The improved stability is evident as the waveform closely resembles the expected reference profile.

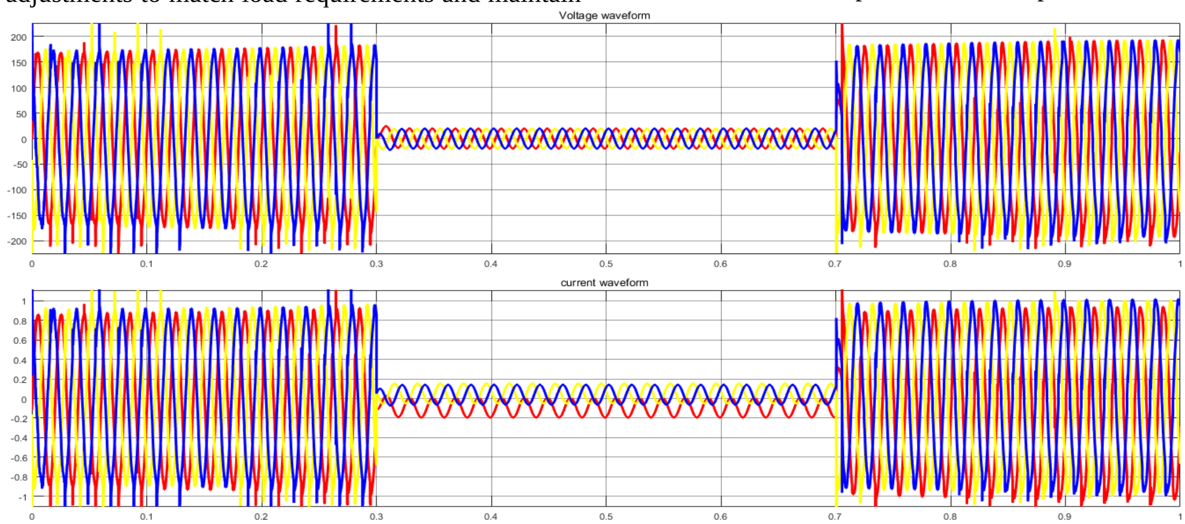

Figure 8 Grid waveform during fault without IPFC

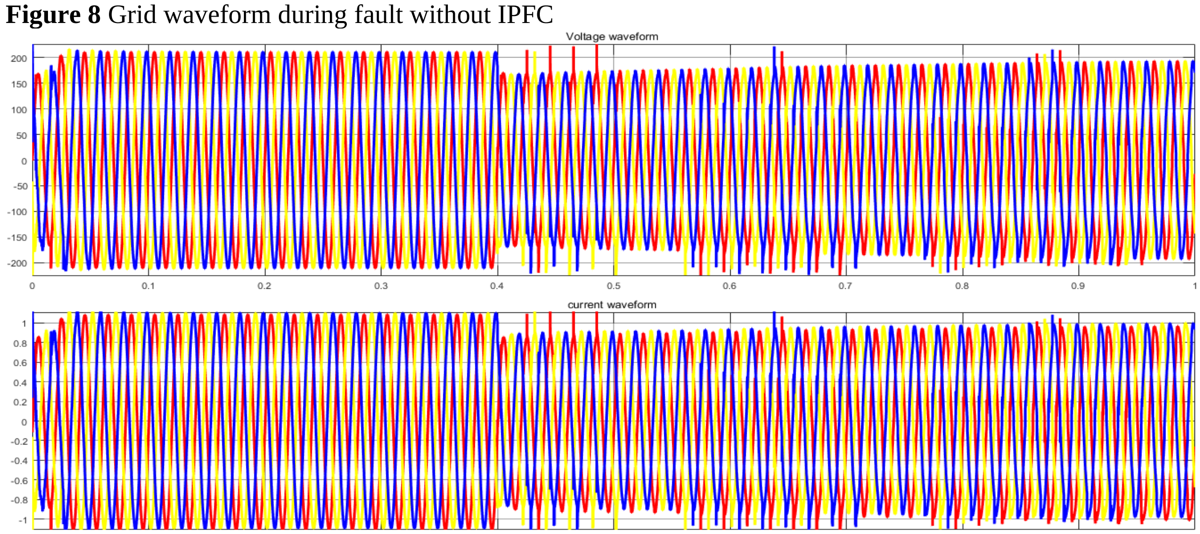

Figure 9 Grid waveform with fault with IPFC

The adoption of an IPFC can dramatically lower total harmonic distortion (THD) levels in the power system. The IPFC's superior control capabilities allow it to reduce harmonics and enhance power quality by actively correcting for reactive power, controlling voltage, and increasing system stability. The IPFC eliminates harmonic distortion in grid waveforms by dynamically altering phase angle and compensating for harmonic currents. This reduces THD percentages, resulting in a cleaner, more sinusoidal grid waveform and better power quality for linked loads. Overall, the introduction of an IPFC helps to reduce THD levels while also ensuring a more efficient and stable power supply. In *Figure 10* and *11*, shows around 9% THD without IPFC and it reduces to 4% while IPFC is connected. A low THD indicates a waveform that is closer to the ideal sinusoidal shape, signifying better power quality and reduced distortion. Conversely, high THD signifies significant harmonic content, leading to a distorted waveform. The overall voltage value in per unit (P.U) from time T1=0.1 seconds is shown in *Figure 12.*

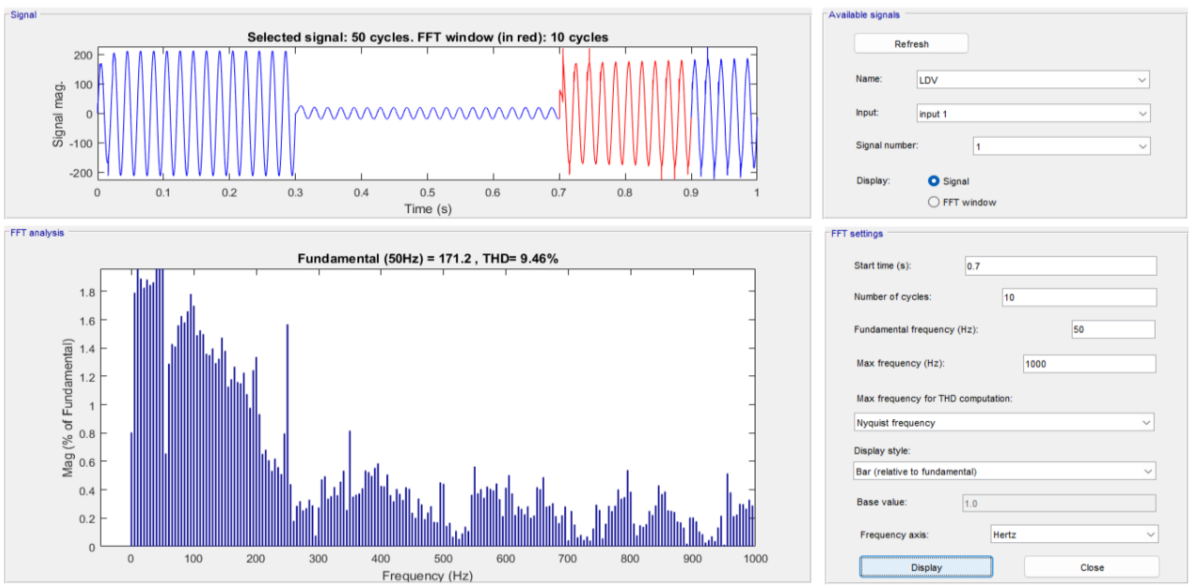

Figure 10 THD without IPFC

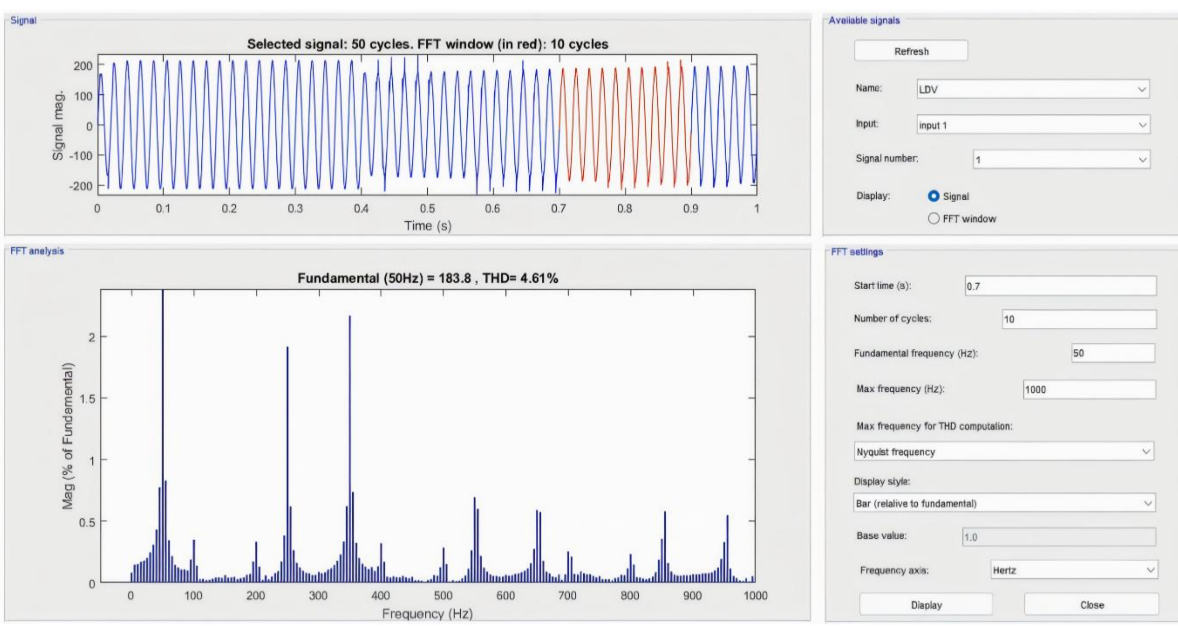

Figure 11 THD with IPFC

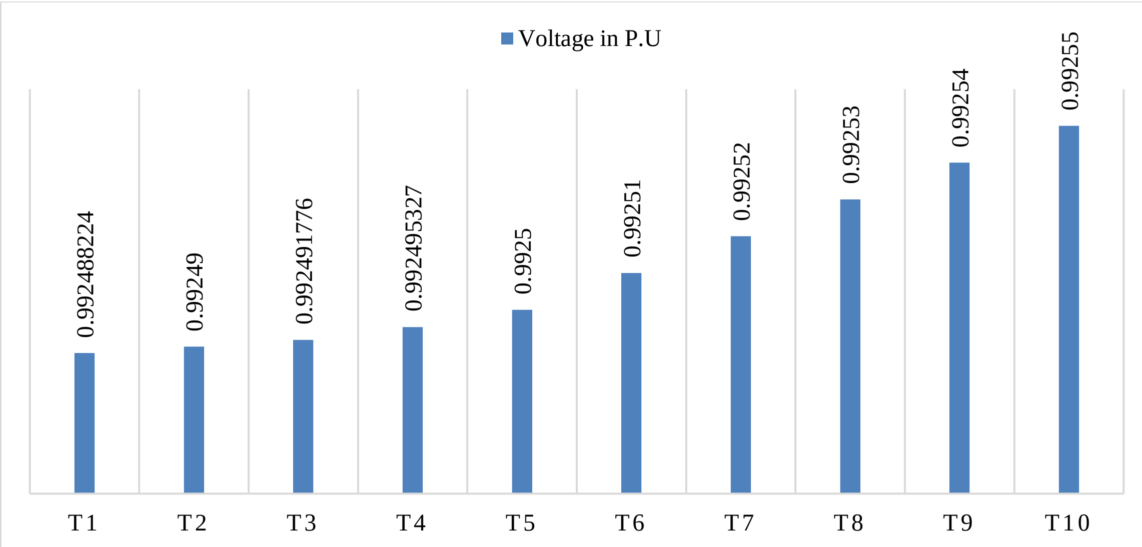

Figure 12 Voltage P.U values for grid connected system

5.Discussions

The total efficiency of a power system, particularly with the integration of an IPFC, reflects optimized energy conversion, reduced losses, improved power quality, and enhanced system management. The IPFC's advanced control capabilities, including power flow optimization, reactive power compensation, and voltage regulation, significantly improve overall performance by minimizing energy losses in transmission and distribution, increasing grid stability, and optimizing energy utilization. By dynamically controlling power flow, reducing voltage fluctuations, and mitigating harmonic distortions, the IPFC ensures a more reliable, stable, and sustainable power supply while optimizing the performance of connected loads. *Figure 13* presents the efficiency results across different trials. In this study, five trials were conducted to evaluate the system's performance and efficiency.

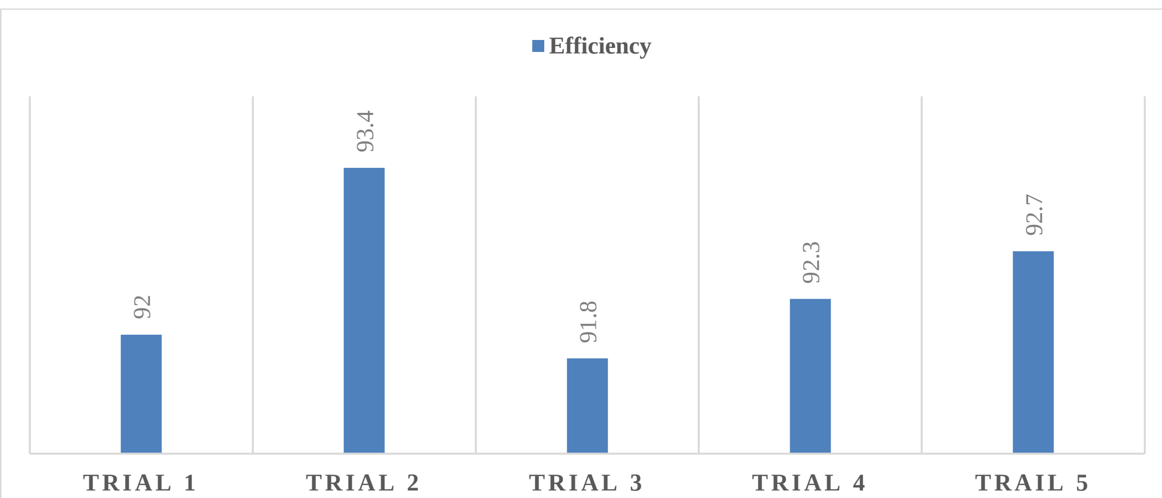

Figure 13 Efficiency of IPFC for different trials

Finally, *Table 4*, compare the proposed method with existing methods. It shows that ANN give higher results in all the parameters. In similar manner *Figure 14*, shows that the overall efficiency of the proposed method is better. Also, the true positive (TP) and true negative (TN) shows the system performance.

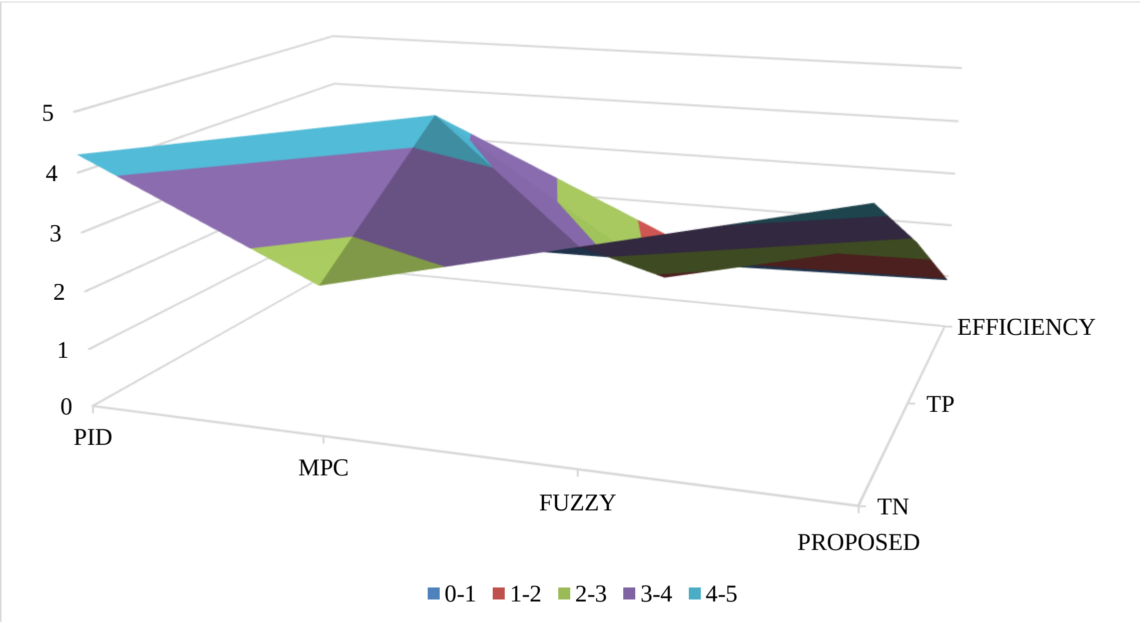

Figure 14 Confusion matrix result for comparison

Table 4 Comparison with existing method

Parameter	Traditional PID [35]	Fuzzy [36]	MPC [37]	ANN [38]
Efficiency	L	M	M	H
Stability	L	M	H	H
Safety	M	H	M	H
OPF	L	M	M	H
L= Low; M= Medium; H= High				

The ANN-based system demonstrated increased resistance to power swings and voltage variations when system stability was evaluated. The ANN system's mean voltage deviation was 3.2%, while MPC, PID, and fuzzy logic had mean voltage deviations of 4.8%, 7.5%, and 5.4%, respectively. This was assessed under various load circumstances during a 24-hour simulation session. The ability of the ANN to dynamically optimize power flow and voltage regulation over time accounts for its exceptional stability.

ANNs outperform traditional methods, such as MPC and fuzzy logic, in dynamic power systems due to their superior computational efficiency, scalability, and adaptability to system changes. Once trained, ANNs can provide real-time predictions and control with minimal computing overhead, delivering responses in under 5 milliseconds. This is substantially faster than MPC, which uses iterative optimization, and fuzzy logic systems, which become more computationally costly as the rule base grows. ANNs are also highly scalable. By adding neurons or layers, they can handle complex high-dimensional inputs without manual adjustments. In contrast, MPC's optimization complexity increases exponentially, whereas Fuzzy Logic systems experience the "curse of dimensionality" as input variables increase.

Limitations

The generalizability of the model is a potential limitation. While the ANN model performed well on the given dataset, it is important to acknowledge that training was conducted using specific grid configurations and operating conditions. Since power grids can vary significantly in terms of topology, load distribution, and fault conditions, the model's ability to generalize to other grid configurations may be restricted. To enhance the model's generalization and robustness, future research could focus on expanding the dataset to include a broader range of grid configurations. However, concerns may still remain regarding the model's adaptability to entirely unknown or highly fluctuating grid conditions.

A complete list of abbreviations is listed in *Appendix I*.

6.Conclusion and future work

The combination of ANN and IPFC technology achieves outstanding efficiencies of 92% or more, marking a paradigm shift in power system control and optimization. Integrating advanced control algorithms and power electronics improves power flow management and transforms modern power grid operations. Leveraging ANN's learning and adaptability, the IPFC surpasses traditional control approaches, enabling intelligent, real-time decision-making in response to grid dynamics and load variations. This synergy allows the IPFC-ANN system to optimize active and reactive power flow, minimize voltage fluctuations, enhance grid stability, and improve overall power quality. The efficiency criterion of 92% or above demonstrates the effectiveness of this integrated approach in minimizing energy losses, decreasing environmental impact, and maximizing the utilization of transmission and distribution assets. Furthermore, the IPFC-ANN integration paves the way for a more intelligent and resilient grid capable of learning, optimizing, and self-healing in response to various operational challenges and risks. This synergy enhances system reliability, reduces maintenance costs, and extends asset lifespan for utility operators while ensuring a stable, high-quality power supply for end users. Despite promising results, the ANN-based approach has limitations. Particularly for large-scale grids, the ANN model's training time can be substantial. Furthermore, there are still issues with the model's generalizability to different grid configurations. Further research is needed to evaluate the model across diverse grid topologies and operational conditions while expanding the training dataset.

Future research on modelling and OPF management in power systems using integrated IPFC and ANN control should focus on several key areas. These include real-time implementation, enhancement of ANN models, integration with other control strategies, multi-objective optimization, large-scale system applications, renewable energy integration, economic feasibility analysis, and cybersecurity measures. Addressing these challenges will facilitate the development of advanced, reliable, and efficient power system technologies, contributing to a more sustainable and resilient energy future.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

None.

Author’s contribution statement

Abhijit Snajay Pande: Conceptualized, wrote, and edited the manuscript, conducted the study, and analyzed the results. **Prakash G. Burade:** Conceptualized and revised the paper, supervised the conducted study, checked the study results and proofread the final corrected version.

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Appendix I

S. No.	Abbreviation	Description
1	AI	Artificial Intelligence
2	ANN	Artificial Neural Network
3	FACTS	Flexible Alternating Current Transmission Systems
4	IPFC	Interline Power Flow Controller
5	LP	Linear Programming
6	MSE	Mean Squared Error
7	MPC	Model Predictive Control
8	OPF	Optimal Power Flow
9	PID	Proportional-Integral-Derivative
10	P.U	Per Unit
11	ReLU	Rectified Linear Unit
12	SSSC	Static Synchronous Series Compensators
13	SQP	Sequential Quadratic Programming
14	THD	Total Harmonic Distortion
15	TP	True positive
16	TN	True Negative