PERIÓDICO TCHÊ QUÍMICA
ARTIGO ORIGINAL

ESTRATÉGIA DE CONTROLE PSO-ANN OTIMIZADA PARA MELHORIA DA QUALIDADE DE ENERGIA EM SISTEMAS HÍBRIDOS DE ENERGIA RENOVÁVEL

OPTIMIZED PSO-ANN CONTROL STRATEGY FOR POWER QUALITY ENHANCEMENT IN HYBRID RENEWABLE ENERGY SYSTEMS

استراتيجية تحكم مُحسَّنة باستخدام خوارزمية تحسين سرب الجسيمات والشبكة العصبية الاصطناعية لتعزيز جودة الطاقة في أنظمة الطاقة المتجددة الهجينة

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RESUMO

Introdução: O rápido crescimento no número de fontes de energia renovável (FER) conectadas à rede elétrica tem gerado um problema significativo de qualidade de energia (QE), com instabilidade de tensão no Ponto de Acoplamento Comum (PAC) devido à sua intermitência. Embora diversos controladores tenham sido propostos para tratar essas questões, um controlador DSTATCOM baseado em Rede Neural Artificial (RNA) para a rede híbrida é comumente utilizado. No entanto, uma RNA autônoma tipicamente perde sua capacidade de manter o controle do DSTATCOM devido à convergência prematura resultante do ajuste subótimo dos pesos durante mudanças repentinas nas condições climáticas. **Objetivo**: Desenvolver um método aprimorado para o ajuste dos pesos de uma RNA, a fim de melhorar sua resposta a variações rápidas na geração de energia renovável, garantindo, ao mesmo tempo, que o controlador opere com êxito sob essas condições. Métodos: Este estudo propõe o uso de um algoritmo de Otimização por Enxame de Partículas (PSO) para otimizar os pesos de ajuste de um controlador RNA-DSTATCOM, visando a regulação da tensão do barramento CC de um Sistema Híbrido de Energia composto por Painéis Fotovoltaicos (PV), Turbinas Eólicas (TE) e geração convencional de eletricidade. O controlador proposto foi implementado e avaliado por meio de simulações em MATLAB/Simulink. **Resultados**: Os resultados foram obtidos a partir de simulações comparando o controlador PSO-RNA proposto com controladores PI e RNA autônomos já existentes. O controlador PSO-RNA apresentou desempenho significativamente superior aos outros dois tipos de controladores em termos de estabilidade do sistema e redução de oscilações. A Distorção Harmônica Total (DHT) medida foi de 2,74% para tensão e 3,37% para corrente, atendendo à conformidade com a norma IEEE 519, além de apresentar uma velocidade de resposta notável e superior na restauração da estabilidade do sistema após eventos de perturbação ou falha. **Discussão**: O desempenho aprimorado do controlador PSO-RNA em comparação com outras soluções é atribuído à capacidade do algoritmo PSO de otimizar eficientemente os pesos da RNA, de modo que o controlador PSO-RNA possa ser mais adaptável às condições variáveis resultantes do uso de fontes de energia renovável. Devido às limitações impostas a este estudo pelos cenários de simulação utilizados, trabalhos futuros incluirão validação física e expansão para sistemas híbridos de maior porte. **Conclusões**: O controlador DSTATCOM baseado em PSO-RNA aqui descrito representa um meio eficiente de aprimorar tanto a qualidade de energia quanto a estabilidade dinâmica de sistemas híbridos de energia renovável.

Palavras-chave: *Rede neural artificial; DSTATCOM; Sistemas híbridos de recursos energéticos (SHRE); Otimização por Enxame de Partículas; Controle PI; Qualidade de energia.*

ABSTRACT

Background: The rapid growth in the number of renewable energy sources (RES) connected to the electrical grid has created a significant power quality (PQ) issue with voltage instability at the Point of Common Coupling (PCC) due to their intermittency. Although several controllers have been proposed to address these issues, an artificial neural network (ANN) based on a DSTATCOM controller for the hybrid grid is commonly used. However, a standalone ANN typically loses its ability to maintain DSTATCOM control due to premature

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convergence caused by suboptimal weight tuning during sudden changes in weather conditions. **Aim**: The goal of this research project is to develop an improved method for tuning the weights of an ANN to enhance its response to rapid changes in renewable energy output while ensuring the controller operates successfully under these conditions. **Methods**: This study proposes using a Particle Swarm Optimization (PSO) algorithm to optimize the ANN-DSTATCOM controller's tuning weights to regulate the DC-link voltage of a Hybrid Power System comprising Photovoltaics (PV), Wind Turbines (WT), and conventionally generated electricity. The proposed controller is implemented and evaluated using MATLAB/Simulink simulations. **Results**: Our results were based on simulations comparing the proposed PSO-ANN controller with existing PI and standalone ANN controllers. The PSO-ANN controller performed far better than the other two controller types in terms of system stability and oscillation reduction. Total Harmonic Distortion (THD) is measured at 2.74% for voltage and 3.37% for current, which meets IEEE 519 compliance while providing a record-breaking, superior response speed that restores system stability after disturbance or fault events. **Discussion**: The improved performance of the PSO-ANN controller compared to other solutions is attributed to the PSO algorithm's ability to efficiently optimize ANN weights so that the PSO-ANN controller can be more adaptable to varying conditions resulting from the use of renewable energy sources. Due to the limitations imposed by the simulation scenarios used, future work will include physical validation and expansion to larger hybrid systems. **Conclusions**: The PSO-ANN-based DSTATCOM controller described here represents an efficient means of enhancing both the power quality and the dynamic stability of hybrid renewable energy systems.

Keywords: *Artificial neural network; DSTATCOM; Hybrid energy resource systems (HRES); Particle Swarm Optimization; PI Control, Power Quality;*

الملخص

الخلفية: أدّى النمو السريع في مصادر الطاقة المتجددة المتصلة بشبكة الكهرباء إلى ظهور مشكلة كبيرة في جودة الطاقة، تتمثّل في عدم استقرار الجهد عند نقطة الربط المشتركة نتيجةً للطبيعة المتقطعة لهذه المصادر. على الرغم من اقتراح العديد من وحدات التحكم لمعالجة هذه المشكلة، إلا أنّ الشبكة العصبية الاصطناعية (ANN) القائمة على وحدة تحكم جهاز التعويض المتزامن (DSTATCOM) للشبكة الهجينة تُعدّ الأكثر استخداماً. ومع ذلك, تفقد الشبكة العصبية الاصطناعية المستقلة عادةً قدرتها على الحفاظ على تحكم DSTATCOM بسبب التقارب المبكر الناتج عن الضبط غير الأمثل للأوزان أثناء التغيرات المفاجئة في الأحوال الجوية. **الهدف:** يهدف هذا المشروع البحثي إلى تطوير طريقة محسّنة لضبط أوزان الشبكة العصبية الاصطناعية لتعزيز استجابتها للتغيرات السريعة في إنتاج الطاقة المتجددة، مع ضمان تشغيل وحدة التحكم بنجاح في ظل هذه الظروف. **طرائق العمل:** تقترح هذه الدراسة استخدام خوارزمية تحسين سرب الجسيمات (PSO) لتحسين أوزان ضبط وحدة تحكم القائمة على ANN-DSTATCOM ، وذلك لتحقيق تنظيم جهد وصلة التيار المستمر لنظام طاقة هجين يتكوّن من الخلايا الكهروضوئية وتوربينات الرياح والطاقة الكهربائية المولدة بالطرق التقليدية. وقد تم تطبيق وحدة التحكم المقترحة وتقييمها باستخدام محاكاة MATLAB/Simulink. **النتائج:** استندت النتائج إلى محاكاة قارنت وحدة التحكم PSO-ANN المقترحة مع وحدات التحكم PI ووحدات التحكم ANN القياسية. وأظهرت وحدة التحكم PSO-ANN أداءً أفضل بكثير من النوعين الآخرين من حيث استقرار النظام وتقليل التذبذبات. كما تم قياس التشوه التوافقي الكلي (THD) بنسبة 2.74% للجهد و3.37% للتيار، وهو ما يتوافق مع معيار IEEE 519، مع تحقيق سرعة استجابة قياسية ومتفوقة لاستعادة استقرار النظام بعد الاضطرابات أو الأعطال. **المناقشة:** يُعزى الأداء المُحسّن لوحدة التحكم PSO-ANN مقارنةً بالحلول الأخرى إلى قدرة خوارزمية PSO على تحسين أوزان الشبكة العصبية الاصطناعية بكفاءة، مما يجعل وحدة التحكم PSO-ANN أكثر قابلية للتكيّف مع الظروف المتغيرة الناتجة عن استخدام مصادر الطاقة المتجددة. ونظرًا للقيود التي فرضتها سيناريوهات المحاكاة المستخدمة في هذه الدراسة، ستتضمن الأعمال المستقبلية التحقق العملي والتوسّع ليشمل أنظمة هجينة أكبر. **الاستنتاجات:** تُمثل وحدة التحكم DSTATCOM القائمة على PSO-ANN، كما وُصفت هنا، وسيلةً فعّالةً لتحسين كلٍّ من جودة الطاقة والاستقرار الديناميكي لأنظمة الطاقة المتجددة الهجينة.

الكلمات المفتاحية : الشبكة العصبية الاصطناعية، جهاز التعويض المتزامن، أنظمة مصادر الطاقة الهجينة، خوارزمية تحسين سرب الجسيمات، متحكم PI، جودة الطاقة.

1. INTRODUCTION:

Today, reliance on Renewable Energy Sources (RES) has become vital for supplying power to underserved populations. Solar and wind energy have generally gained more global attention because they are plentiful and sustainable (Das *et al*., 2022). When connecting RES to the utility grid, challenges arise regarding PQ issues such as voltage sags/swells, THD, and changes in power factor (Sahoo *et al*., 2023; Ranjan *et al*., 2024). These problems are caused by the intermittent nature of RES, which can make the grid as a whole unstable (Habib *et al*., 2025). Power compensation devices that help overcome some of these problems include UPQC, SVC, DVR, and DSTATCOM (Jha & Shaik, 2023). However, DSTATCOM is regarded as the most beneficial of these devices due to its cost-effectiveness, compactness, and efficient reactive power support (Etanya *et al*., 2025). The performance of any power compensation device is influenced by how the function of the compensator is controlled. On the other hand, while traditional controllers are easy to implement, they struggle to maintain stability over long periods due to fluctuations in renewable energy generation (Choudhury & Kumar, 2024). There is a need for advanced intelligent controllers that respond to changes dynamically and provide high reliability.

Many control techniques have been tested recently to improve the performance of DSTATCOM technology in hybrid systems. Historically, Conventional Controllers (Especially the PI Controller) have been the most common controller types used because they are easy to use and implement (Raju *et al*., 2019). However, the main drawback of Conventional Controllers is that they are difficult to tune the proportional and integral gain parameters to maintain stability under highly nonlinear and dynamic load conditions. Hence, researchers have turned to Fuzzy Logic Controllers (FLC) as a better alternative that does not require an exact mathematical model of the system (Rajshekar *et al*., 2025).

The problem with FLC is that its performance depends on the designer's knowledge of how to define the rule base and membership functions, thereby creating a high computational cost for complex systems. Another improvement in this area has been to use Optimization Algorithms to help fine-tune the traditional controllers' parameters. Khadse and Beohar (2024), Alwaeli *et al*. (2025), Srilakshmi *et al*. (2025), and Hammad *et al*. (2023) used algorithms to significantly improve the transient responses of PI Controllers. Even though these methods provided improved performance, no method exists to provide sufficient adaptability to account for the random variation found in renewable energy resources.

As a result, the emphasis has shifted to using AI techniques, especially ANNs, as they are best at learning and adapting to changes in a system (Bousbai, 2026; Hemalatha & Ramasamy, 2020; Sah & Singh, 2023). The latest research indicates an increasing trend toward hybrid intelligent systems to achieve maximum accuracy. By using optimization algorithms with AI models for training and weight optimization, some researchers have achieved improved control performance (Zaro, 2021). Table 1 shows the literature comparison.

While advancements have been made in control strategies for power electronics, several important gaps remain in the literature. Firstly, there is a lack of a systematic methodology for optimizing ANN architectures. Consequently, they are typically deployed without systematic refinements, resulting in limited stability across the entire system. Often, current research either focuses on PI controllers that do not perform well under nonlinear disturbances or completely replaces them with complex AI-type controllers, thereby imposing a significant computational burden and a high implementation cost without differentiating between critical and non-critical control loops. Secondly, the interaction between regulating the DC-link voltage in RES generation, such as a PV system, and operating DSTATCOMs has received very little research attention; therefore, the potential effects this interaction could have on PCC voltage stability during both transient and dynamic events have not been fully explored.

1.1. Aims

To address these challenges, this study contributes to the field by developing a selective control strategy that replaces conventional controllers in the critical DC-link voltage loops of the PV system and the DSTATCOM with an intelligently optimized ANN. The PSO algorithm is employed to develop the optimal ANN structure and weights in a systematic manner, thereby significantly improving the stability and dynamic response of the PCC voltage.

Moreover, these improvements are achieved with minimal additional system complexity by continuing to use traditional controllers in non-critical loops. Thus, the main contribution of the present research is not only to implement an ANN optimization based on PSO but also to introduce a selective control deployment that balances performance improvement and practical implementation in hybrid renewable energy systems. Comparative simulations are performed to evaluate the effectiveness of the proposed control strategy relative to traditional PI and standard ANN controllers under multiple dynamic operating scenarios, including voltage sag and swell disturbances, simultaneous variations in renewable energy generation sources, and single-line-to-ground faults. The results obtained are used to quantitatively demonstrate the impact of the proposed control strategy on PCC voltage stability and power quality. The remainder of this paper is structured as follows: Section 2 details the System Configuration. Section 3 explains the Proposed PSO-ANN Control Strategy. Section 4 presents and analyzes the Results and

Discussion, and Section 5 provides the Conclusion of the study.

2. MATERIALS AND METHODS:

2.1. Materials

The system being researched is a grid-tie hybrid power generation system that combines renewable energy technologies (PV and WT) with a traditional electrical grid supply. A DSTATCOM is used at the point of connection between the grid and the hybrid system to provide power-quality improvements (through reactive power control) and maintain voltage stability as operating conditions vary. This overall system is modeled and simulated using MATLAB/Simulink. To facilitate the development and evaluation of Intelligent Controllers, a dataset consisting of 9000 sample points was created based on analyzing the steady-state response of the hybrid system when operating with a standard analog PI Controller. This data set is then utilized to train and validate the ANN-based Controllers. The technical systems parameters used in the simulations are summarized in Table 2.

2.2. Methods

2.2.1. System Configuration

The architecture of the hybrid system evaluated in this paper is depicted in Fig. 1. The hybrid system comprises two main renewable energy sources, i.e., a solar PV system and a wind energy conversion system. It provides power to the electric utility grid and support load growth, with the intent of supporting the electric utility grid in its ability to accommodate the increase in electric load demand on the utility grid, taking advantage of the facts that solar and wind energy sources are two of the most reliable and sustainable forms of renewable energy sources (Parija *et al*., 2019). A DSTATCOM is used to provide voltage regulation at the PCC. The primary purpose of the hybrid system is to determine the interactions among the renewable energy sources and the effectiveness of the control strategy in maintaining PCC stability (Taya *et al*., 2024). Solar energy systems convert sunlight into electrical energy (solar irradiance), and the amount of electricity produced depends on the intensity of sunlight. Moreover, wind energy systems use wind to extract kinetic energy and generate electricity. The output of wind energy systems also varies with wind speed. Both solar and wind have problems due to fluctuations in sunlight and wind. Therefore, they both contribute to continuous variations in active power, leading to issues with voltage stability, reactive power imbalance, and increased THD at the PCC. A DSTATCOM can help resolve these issues through dynamic reactive power compensation and voltage regulation (Prasad *et al*., 2026). The DSTATCOM's performance will be based on the controller used to regulate the inverter output, which controls both the inverter output voltage magnitude and phase angle to adjust the amount of reactive power injected into or withdrawn from the grid. The amount of reactive power exchanged with the grid can be expressed mathematically as in Equation 1:

$$Q = \frac{V_1(V_1 - V_2 cos\alpha)}{Z} \quad \text{(Eq. 1)}$$

where $V1$ is the grid voltage, $V2$ is the inverter output voltage, Z is the coupling impedance, and α is the phase angle between the voltages. Proper control of $V2$ and α allows effective voltage regulation and improved power quality. To achieve this in the synchronous dq reference frame, the AC terminal voltage regulation is managed by calculating the error according to Equation 2:

$$V_{err}(n) = V_{ref} - V_{actual}(n) \quad \text{(Eq. 2)}$$

This error is processed by an outer PI controller to generate the reference quadrature current $Iqref$ as Equation 3:

$$Iq_{ref}(n) = Iq_{ref}(n-1) + K_p\{V_{err}(n) - V_{err}(n-1)\} + K_i V_{err}(n) \quad \text{(Eq. 3)}$$

where Kp and Ki are the proportional and integral gain constants. The Iq from the abc to dq conversion is done using Park Conversion on all the supply currents. Then, it analogizes Iq and $Iqref$, and uses that to feed an inner Switched PI current controller that generates Vq (Equations 4 and 5).

$$I_{qerr}(n) = I_{qref}(n) - I_q(n) \quad \text{(Eq. 4)}$$

$$V_q(n) = V_q(n-1) + K_p\{I_{qerr}(n) - I_{qerr}(n-1)\} + K_i I_{qerr}(n) \quad \text{(Eq. 5)}$$

Simultaneously, the stabilization of the DC-link voltage Vdc is critical for maintaining the required inverter performance. The DC voltage error is defined in Equation 6:

$$V_{dcerr}(n) = V_{dcref} - V_{dc}(n) \quad \text{(Eq. 6)}$$

This error is processed by an outer PI controller to generate the reference quadrature current $Idref$ as Equation 7:

$$I_{dref}(n) = I_{derf}(n-1) + K_p\{V_{dcerr}(n) - V_{dcerr}(n-1)\} + K_i V_{dcerr}(n) \quad \text{(Eq. 7)}$$

The Id from the abc to dq conversion is done using Park Conversion on all the supply currents. Then, it analogizes Id and $Idref$, and uses that to feed an inner Switched PI current controller that generates Vd. Equations 8 and 9.

$$I_{derr}(n) = I_{dref}(n) - I_d(n) \quad \text{(Eq. 8)}$$

$$V_d(n) = V_d(n-1) + K_p\{I_{derr}(n) - I_{derr}(n-1)\} + K_i I_{derr}(n) \quad \text{(Eq. 9)}$$

Traditionally, a PI controller is used to DC-link voltage regulation for both the PV system and the grid-connected DSTATCOM due to its simplicity. However, its performance is sensitive to parameter tuning and may degrade under rapid fluctuations in renewable generation. ANNs can improve control, but a standard ANN alone cannot solve many dynamic control problems across a wide range of operating conditions. Therefore, this research proposes an ANN optimized using PSO. The PSO-ANN will provide enhanced system response and power quality for any dynamic control application, as discussed in the subsequent sections of the paper.

2.2.2. Proposed PSO-Optimized ANN Control Strategy

To enhance the dynamic performance of the hybrid system, the PSO algorithm is applied with an ANN control strategy proposed to regulate the DC-link voltage of both the PV system and the DSTATCOM. Accurately and quickly regulating DC voltage is very important for the safe operation of the inverter and for providing sufficient reactive power. To achieve this, the dataset used to train the ANN controller was generated from simulation results of the conventional PI controller under different disturbance conditions. A total of approximately 9,000 sample values were collected from both steady-state and transient responses of the DC link voltage. This sample was split into three portions: 70% for training, 15% for validation, and 15% for testing. The ANN inputs are the DC-link voltage error and its derivative, while the output is the control signal applied to the voltage regulation loop. The PSO algorithm was implemented in two phases to optimize both the ANN architecture and its connection weights. The PSO was configured with a swarm size of 30 particles, a maximum of 100 iterations, acceleration coefficients C1 = 1.5 and C2 = 1.5, and an inertia weight of 0.7. The first phase of optimization used PSO to determine an optimal network topology by calculating the number of hidden neurons that yielded the lowest mean squared error (MSE). This optimal structure consisted of two hidden layers: the first with 18 neurons and the second with 28.

After modifying the network topology, the ANN weights were optimized using PSO to improve convergence and dynamic performance (Figure 2). As shown in Table 3, the final reported MSE provides a good representation of the overall optimization process and shows the minimum error achieved by this combined search for both architecture and weights. The PSO-ANN control is subsequently implemented in the system as the replacement for the conventional

PI Controller. Compared to the fixed-parameter PI controller, the proposed PSO-ANN benefits from better adaptability to different solar irradiance and wind speed conditions. Therefore, this results in quicker DC-link voltage stabilization, less overshoot, and overall improvement to the performance of the DSTATCOM to mitigate power quality disturbances. Fig. 3. summarizes the selection of controls in the proposed methodology.

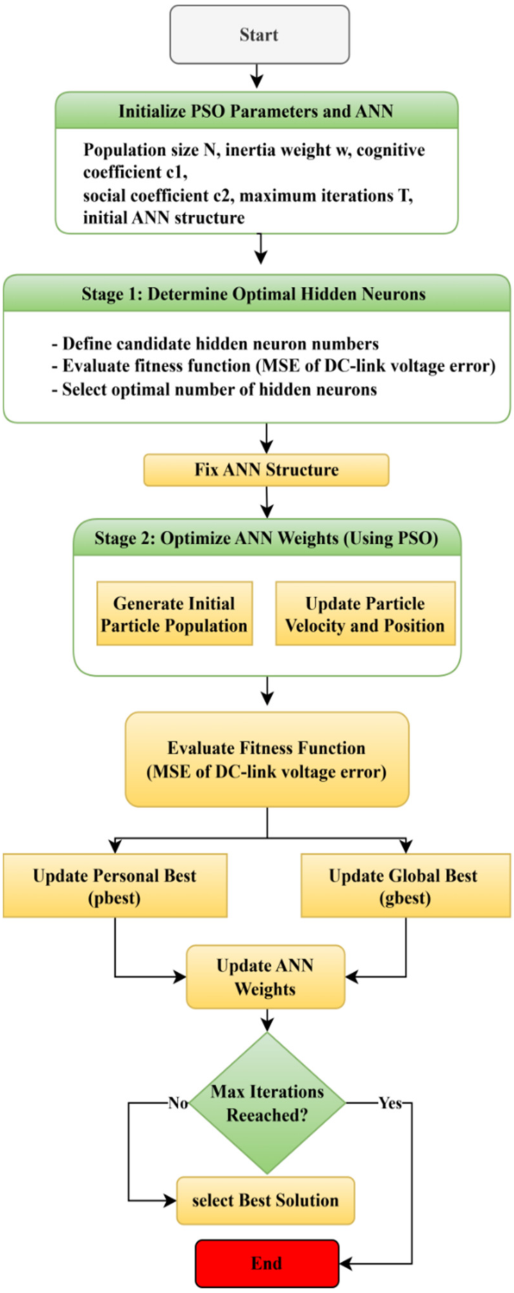

Figure 2. Flowchart of the PSO-ANN algorithm

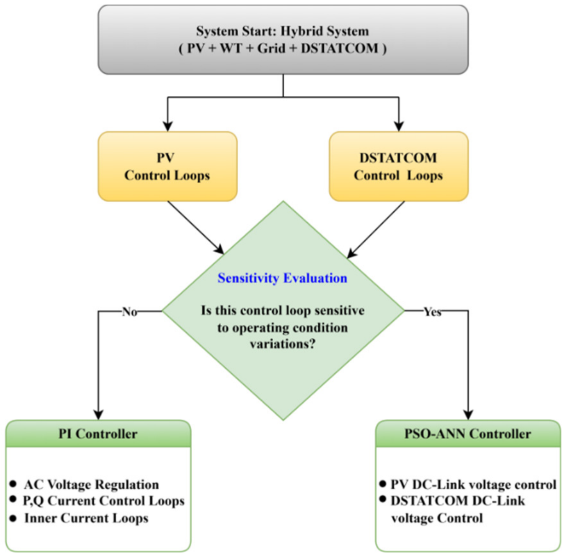

Figure 3 . Proposed hybrid control system.

2.2.3. Controller Tuning and Comparison Setup

To compare the controllers fairly, all controller operations occurred under the same system model, disturbances, and simulation conditions. Conventional PI-controller parameters were tuned using standard methods to achieve stable regulation of the output DC-link voltage under nominal operating conditions, with no variation or noise in the input variables. In contrast, a standard-tuned ANN controller was trained on data generated from the PI-based system's responses, without utilizing PSO optimization techniques. The proposed PSO-ANN controller uses PSO to find an improved set of ANN parameters; therefore, this setup allows for a performance comparison that reflects changes in performance due to differences in the optimization process.

2.2.4. Statistical Analysis

Because the results come from deterministic simulations, no traditional statistical testing will be performed. Assessments will instead be made based on engineering performance metrics. The performance of the controller will be compared with other controllers using standard indices such as THD and the Integral of Time-weighted Absolute Error (ITAE). Both of these indices are commonly used to classify the amount of waveform distortion and the transient response performance of an electrical system.

The ITAE is defined as Equation 10:

$$ITAE = \int_0^T t|e(t)|dt \quad \text{(Eq. 10)}$$

where e(t) is the error between the desired and the actual measured voltage of the DC-link, and T is the total time that the simulation was run. The ITAE penalizes errors that persist for extended periods, which makes it a good indicator of transient response.

The THD is computed as follows:

$$THD = \sqrt{\sum_{n=2}^{\infty} \frac{V_n^2}{V_1}} \times 100\% \quad \text{(Eq. 11)}$$

where V_1 is the fundamental component, and Vn represents the harmonic components of the voltage or current. The THD is used to quantify the degree of harmonic distortion in an electrical system.

All test data were obtained from simulation output files, and none were missing. Lower values of THD and ITAE indicate better power quality and a more rapid dynamic response, respectively.

3. RESULTS AND DISCUSSION:

3.1. Results

The proposed control approach has been demonstrated through simulation results to be capable of addressing power quality issues in grid-interconnected hybrid systems. The proposed controller is well-suited to handle dynamic fluctuations in renewable generation sources and disturbances at the PCC, such as voltage fluctuations and faults, thereby enhancing system stability at the PCC level. Regarding harmonic performance, the proposed controller achieved a THD of 2.74% for voltage and 3.37% for current. Both of these THD values meet the IEEE 519 limits on THD and therefore indicate that the power quality provided to the system during testing met acceptable standards. In addition, the proposed controller provides a much more stable voltage profile and a significantly improved dynamic response than other control methods, as evidenced by reduced oscillations and quicker recovery from disturbances. The core findings from the various testing scenarios are summarized quantitatively in Table 4.

3.2. Discussion

This study assesses both the evaluation of the methodology applied and the effect that the use of this new methodology has on improving power quality and maintaining system stability. The hybrid generation system consists of PV/WT connected to the utility grid, with DSTATCOM connected at the PCC. The simulations are performed in MATLAB/Simulink to evaluate the proposed control strategy against a conventional PI controller and ANN methods. To demonstrate that the proposed control method works across various operating conditions, several scenarios reflecting typical grid-connected power system operation are simulated.

3.2.1. DSTATCOM performance during a voltage swell and sag

Using a programmable AC power source in MATLAB/Simulink, our proposed methodology is tested with voltage sags and swells. A voltage swell occurs from 0.2s to 0.3 s, followed by a voltage sag from 0.3s to 0.4s (as shown in Figure 4(a)), demonstrating how D-STATCOM plays an important role by either absorbing or injecting reactive power into the system to reduce fluctuations caused by these disturbances. When voltage sags occur, the DSTATCOM operates in capacitive mode to inject reactive current into the system and help stabilize the voltage. When voltage swells occur, the DSTATCOM uses inductive mode operation to absorb excess reactive power from the system (acting as an inductor) as shown in Figure 4(b). The effectiveness of reactive power compensation from the DSTATCOM is evidenced by the rapid return to steady-state, with minimal oscillation, of the voltage at the PCC following each disturbance (as shown in Figure 4(c)).

3.2.2. Performance Under Concurrent Dynamic Disturbances

This examination tests the proposed approach's ability to handle multiple simultaneous disturbances and reflects challenging, typical operating environments. The solar radiation decreased rapidly from 1000 W/m² to 800 W/m² at t = 1 s and returned to 1000 W/m² at t = 1.5 s. Parallel to this decrease, wind speed increased instantaneously from 15 m/s to 20 m/s at t = 1.5 s, along with an additional load change at t = 2 s. The voltages at the PCC in Fig. 5 show that the PSO–ANN approach had the least voltage overshoot and the fastest settling time across all scenarios for voltage control. The PSO-ANN approach also had a greater ability to compensate for reactive power, as illustrated in Fig. 6. In addition to these tests and the voltage sag/swell disturbances, the proposed controller successfully reduced the THD to 3.37% for current and 2.74% for voltage. These values not only exceed the performance of traditional controllers but also comply strictly with the IEEE 519 international standards. Thus, it can be concluded that the proposed system improves power quality and produces a pure sine wave even during many dynamic operational changing conditions.

3.2.3. Performance Under Single-Line to Ground Fault

The testing is designed to confirm the performance of the system and control algorithm in terms of dynamic response to a Single Line-to-Ground (SLG) fault, which commonly occurs. An SLG fault is simulated from t = 0.2 seconds to t = 0.3 seconds to evaluate how quickly the D-STATCOM and controllers can provide reactive power to mitigate the voltage sag caused by the SLG fault and return the system to normal as soon as the fault is cleared. The performance of the system during the pre-fault, fault, and post-fault periods is illustrated in Fig. 7. During the SLG fault, the D-STATCOM effectively alleviates the voltage drop by providing the required reactive power with very good accuracy. The PSO-ANN controller shows a slightly faster recovery from the SLG fault, with a total settling time of 0.01386 seconds after the fault is cleared, while some controllers require approximately 0.014005 seconds to reach steady-state. Although the numerical difference is relatively small, the results consistently indicate that the optimized PSO-ANN controller provides a slightly faster recovery under the studied disturbance conditions.

4. CONCLUSIONS:

In this work, a new integrated DSTATCOM system employing a hybrid PSO-ANN algorithm is proposed to improve power quality in modern power systems. The work included the creation and simulation of a hybrid power system comprising PV, wind, and a conventional source, connected to a utility grid at the PCC. The DSTATCOM is installed as the primary measure for reactive power compensation and voltage stabilization at PCC to help overcome dynamic challenges. The main contribution of this work is the use of a "multiple-selective-level control strategy," in which traditional PI controllers are used for non-critical control loops due to their simple functionality and low processing time. Similarly, the optimized PSO-ANN intelligent controller is positioned to control the most important loops (i.e., the DC Link voltage control that serves both the PV system and the DSTATCOM), critical to ensuring that the entire integrated system operates at an acceptable level of stability. Through comprehensive simulation tests under a range of dynamic conditions, including load changes and faults, the proposed controller demonstrates improved performance compared with conventional PI and standard ANN controllers. The results indicate that a significant reduction in THD to 2.74% for voltage and 3.37% for current is required to be fully compliant with IEEE 519 standards. Future, it shows the ability to quickly restore the stability of the hybrid system after a fault, achieving this within 0.01386 sec, slightly quicker than that of the standard ANN (0.013875 sec) and conventional PI (0.014005 sec) control methods. Thus, the results indicate that the proposed theory provides a computationally efficient means of stabilizing complex hybrid power systems.

5. DECLARATIONS

5.1. Study Limitations

Methodological limitations: This study relies entirely on deterministic simulations performed in MATLAB/Simulink. The system models employ idealized component parameters and do not account for real-world non-idealities such as switching losses, electromagnetic interference, measurement noise, or communication delays between controllers.

Limitations in sample size: The ANN training dataset comprises approximately 9,000 sample points derived exclusively from the steady-state and transient responses of a conventional PI controller. This dataset may not capture the full range of dynamic operating conditions encountered in real hybrid power systems, potentially limiting the generalization capability of the trained network.

Resource or equipment limitations: No Hardware-in-the-Loop (HIL) testing or physical prototype validation was conducted. All results are based on software simulation, and the actual performance of the PSO-ANN controller in a real-time embedded environment remains unverified.

Generalizability limitations: The proposed controller was evaluated on a single hybrid system configuration (2 MW PV, 2 MW WT, 3 MVAR DSTATCOM, 25 kV grid). Its performance under different system scales, network topologies, higher penetration levels of renewable energy, or alternative renewable sources (e.g., biomass, small hydro) has not been investigated. Additionally, only balanced three-phase load conditions and a limited set of fault types (voltage sag/swell, SLG fault) were considered.

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In accordance with the ethical guidelines of the Periódico Tchê Química, which do not allow donations from authors with manuscripts under evaluation (even when research funds are available), or in cases of authors' financial constraints, publication costs were fully absorbed by the journal under our Platinum Open Access policy, through the support of the Araucária Scientific Association (https://acaria.org/). This policy aims to ensure complete independence between the editorial process and any financial aspects, reinforcing our commitment to scientific integrity and equity in knowledge dissemination.

5.4. Conflicts of Interest

The authors declare no conflict of interest and no competing interests.

5.5. Data Availability

All data presented in this study are available in the manuscript tables and figures. Raw data are available upon request from the corresponding author.

5.6. Author Contributions

M.S.A.-O is the main author who conducted the system design and simulations. At the same time, S.D.A.-M. is supervising the research.

5.7. AI and Computational Tools Declaration

The authors declare that they used the generative AI tool Gemini by Google solely to assist with grammar and style improvement and to format figures and tables in this document; any AI-generated outputs were reviewed, verified, and significantly revised by the authors. No AI was used for data generation, statistical analyses, or scientific interpretation of data. The authors retain complete responsibility for the final content of this report and the truthfulness and integrity of this research.

5.8. Research Integrity Declaration

The authors confirm that the work presented in this article is original research and has not been published previously. The authors state that all simulation data and results were generated honestly, without fabrication, falsification, or selective reporting. Each method was performed in accordance with the appropriate research ethics and integrity standards at the time of this study.

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5.9. Originality & Plagiarism Statement

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5.10. Open Access License

6. Ethics Committee Approval

6.1. Ethics Committee Approval

Not applicable (N/A). This research is a simulation-based study using MATLAB/Simu_ link and does not involve any experiments on human participants or animal subjects. Therefore, ethical approval was not required.

6.2. Informed Consent

Not applicable.

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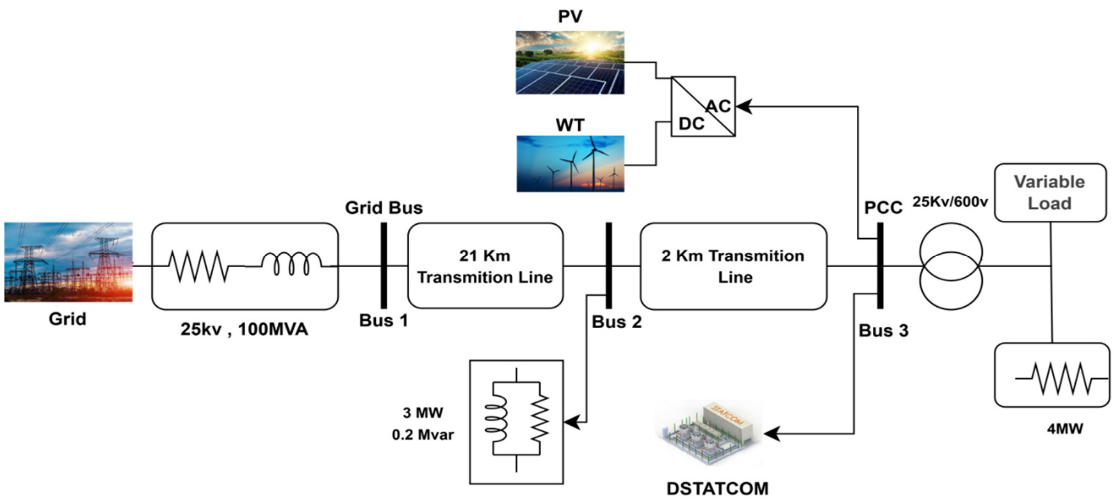

Figure 1. *Proposed hybrid system configuration*

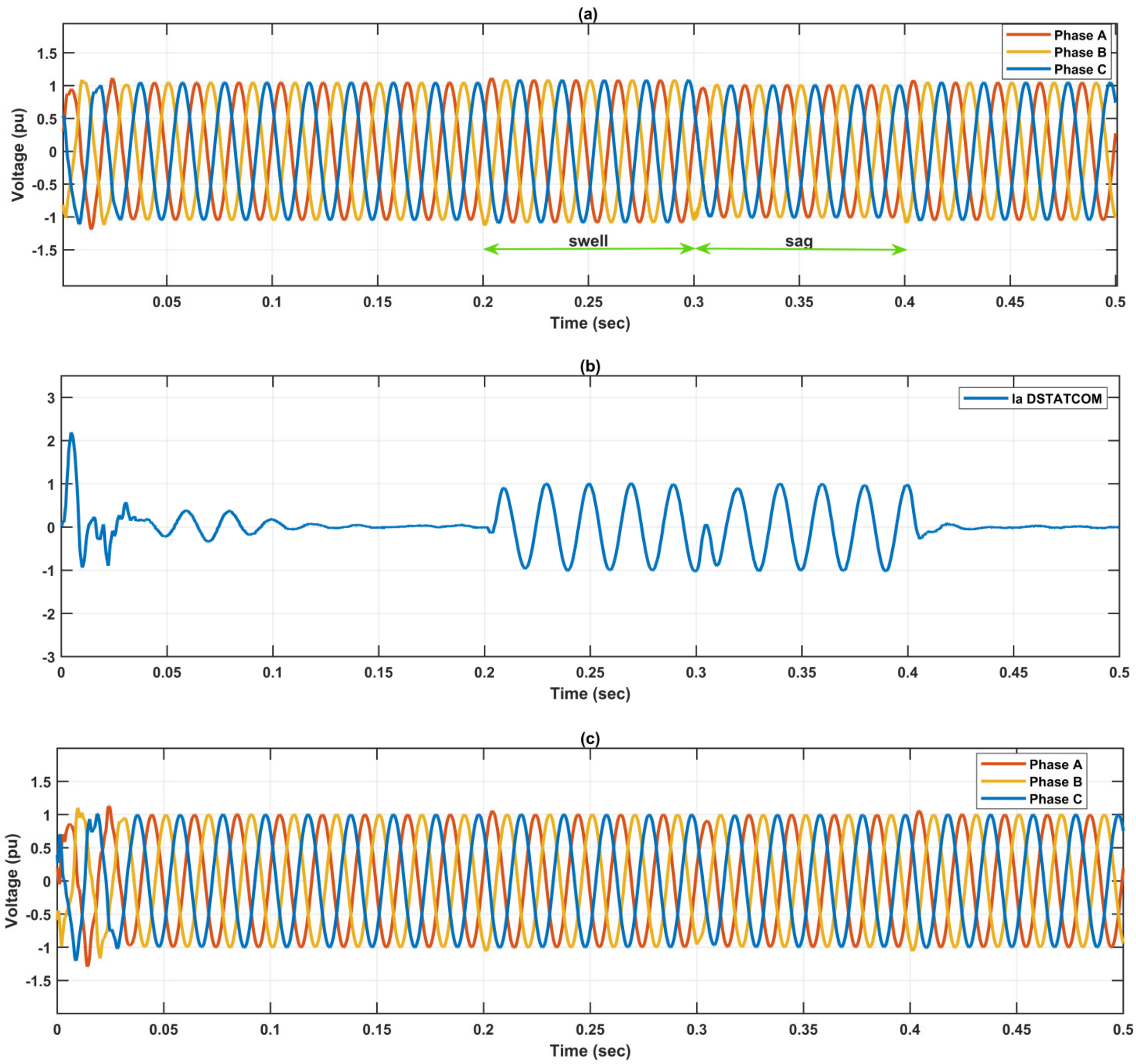

Figure 4. *a) voltage source, (b) injected current, and (c) voltage load*

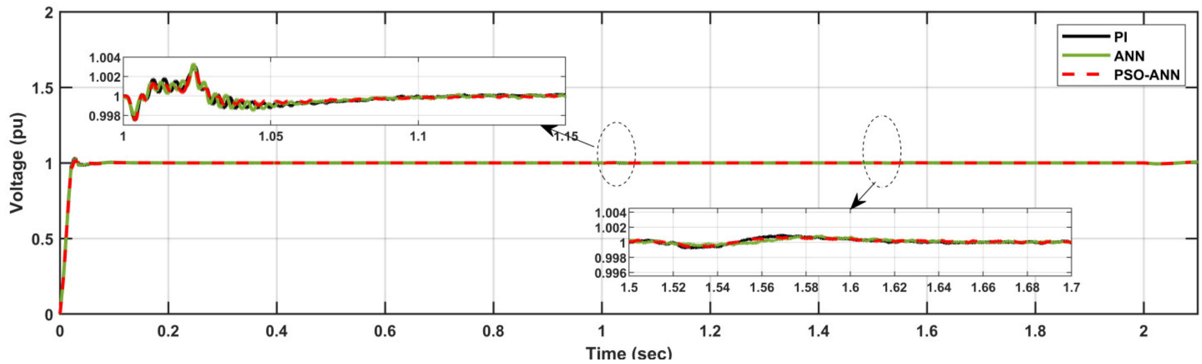

Figure 5. *PCC voltage response comparing three controllers*

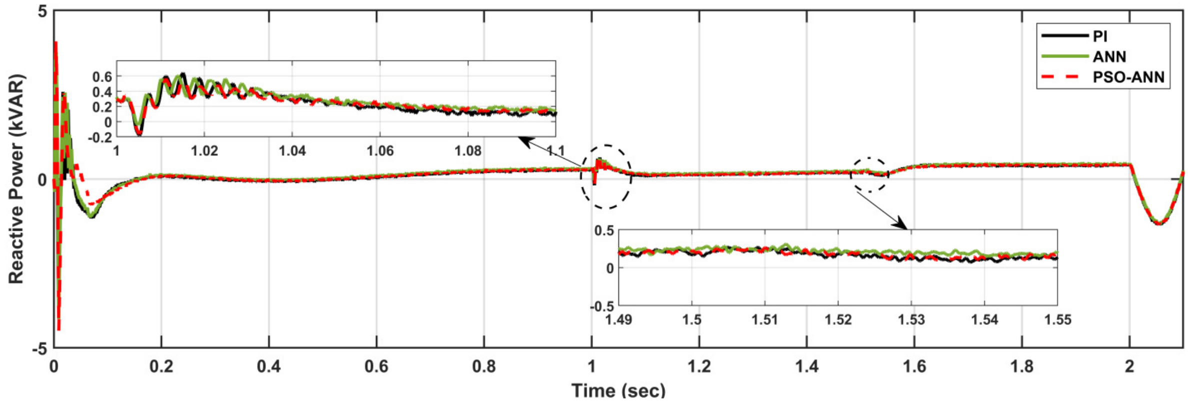

Figure 6. *Reactive Power PCC voltage response comparing three controllers*

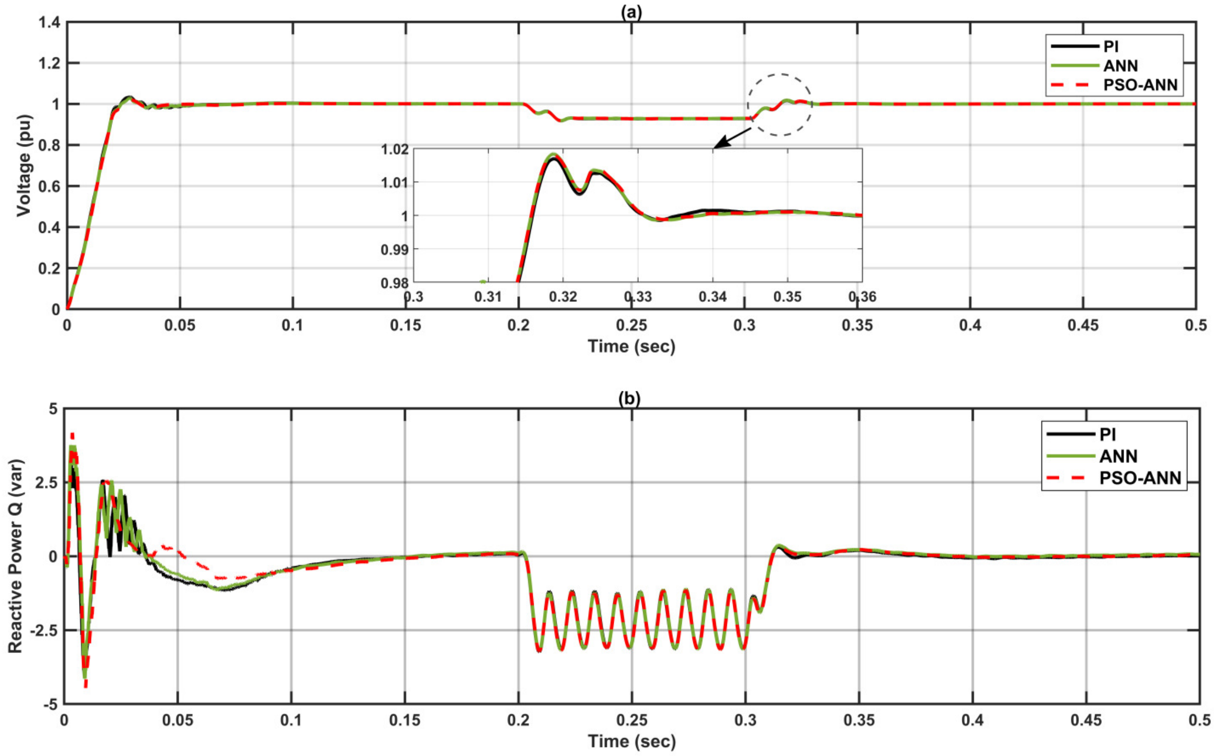

Figure 7. *System performance during SLG fault (a) PCC voltage response in (pu), (b) Reactive power injection for fault recovery*

***Table 1.** Literature comparison*

Ref.	Control Method	Key findings	Limitations
(Raju *et al.*, 2019)	PI Controller	Successfully compensated for reactive power, stabilizing the grid through projects completed using PSCAD/EMDTC.	Slow response during disturbances
(Rajshekar *et al.*, 2025)	fuzzy PID-controlled	Reduced grid and load currents' THD to under 0.15% and 0.02%, respectively, while improving MPPT extraction from wind-BESS systems.	Complex rule design
(Alwaeli *et al.*, 2025)	GWO-PI controlled	Maintained PCC within a range of 0.92 and 0.97 pu during three-phase faults, enabling improved dynamic response.	Better than manual PI, but still struggles with nonlinear stochastic solar/wind changes.
(Khadse & Beohar, 2024)	WdCH-PI controlled	Used the Weighted Chimp Optimization method to optimize the fundamental weights of load currents in improving PQ for either balanced or unbalanced loads.	Using traditional distribution networks that have not been validated against the uncertain intermittency of hybrid renewable energy sources (both PV and WT).
(Hemalatha & Ramasamy, 2020)	Standard ANN	Implemented constant DC-link voltage, reduced harm output versus using traditional PI and fuzzy controllers.	Depends on training data quality
(Sah & Singh, 2023)	DBN-CNN	Used Deep Belief Nets and Convolutional Networks to perform advanced levels of harmonic feature extraction for the purpose of reducing harmonic levels.	Cost estimates were based on much larger data sources, and diverse and new scientific methods were used to collect real-time implementation data for this project. A hybrid renewable energy source system has never been utilized within this concept.
Proposed work	PSO-ANN	Successfully balanced ease/low cost of implementation versus accuracy of performance, generating THDv of 2.74% and THDi of 3.37% (per IEEE 519). Achieved high speeds, while minimizing oscillations.	Current validation is restricted to simulation environments. future work requires Hardware-in-the-Loop (HIL) implementation and real-time experimental testing.

Table 2. *Parameters of the System*

	System Parameters	Value
	Main Grid	25 kV,50Hz
PV	Total Capacity	2MW
	DC Voltage set point	1200 V
WT	WT	2MW
	Tr. PV	480 V/ 25 kV
	Tr. WT	575 V/ 25 kV
	Tr. Load	25 kV / 600 V
	Linear load	4 MW, 0.2MVAR; 600 V
DSTATCOM	Source Power	3 MVAR
	DC Voltage set point	2400 V
	Line Resistance	0.12Ω
	Line Inductance	0.0039H
	DC Link Capacitance	10 mF
PI Controller parameters	AC Voltage Regulator	K_P=0.55, K_I=2500
	DC Voltage Regulator	K_P=0.55, K_I=2500
	Current Regulator	K_P=0.8, K_I=200

Table 3. *Training performance comparison between ANN and PSO-ANN*

Algorithm	Hidden (L1)	Hidden (L2)	Total Epochs	Final MSE
ANN	20	-	116	0.0034904
PSO-ANN	18	28	130	0.002443

Table 4. *Comparative System Performance Results*

Performance Parameter	Conventional PI	Standard ANN	Proposed PSO-ANN
THDv	3.15%	3.10%	2.74%
THDi	3.47%	3.46%	3.37%
Settling Time after Fault	0.014005s	0.013875s	0.01386s
ITAE	5.0719e-06	5.0122e-06	4.6594e-06

List of abbreviations

Full From	Abbreviation
Artificial intelligence	AI
Artificial neural network	ANN
Convolutional Neural Network	CNN
Deep Belief Network	DBN
Dynamic Voltage Restorer	DVR
Dynamic Static Compensator	DSTATCOM
Grey Wolf Optimization	GWO
Particle Swarm Optimization	PSO
Photovoltaic	PV
Point of common coupling	PCC
Power quality	PQ
Proportional-Integral	PI
Static VAR Compensator	SVC
Total Harmonic Distortion	THD
Unified Power Quality Conditioner	UPQC
Weighted Chimp Optimization Algorithm	WdCH
Wind Turban	WT