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ANN CONTROLLER FOR PREDICTIVE CONTROL OF PMSG-BASED HYDRO-ELECTRIC GENERATION WITH BATTERY-SUPPORTED UPQC

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ABSTRACT
This research introduces an Artificial Neural Network (ANN)-based predictive control approach for hydroelectric power generation using Permanent Magnet Synchronous Generators (PMSG) integrated with a battery-supported Unified Power Quality Conditioner (UPQC). The proposed control system is designed to enhance power quality, ensure voltage and frequency stability, and maintain smooth grid interaction under dynamic load and source variations. The ANN controller is employed within the predictive control framework to optimize UPQC switching, enabling rapid response and robust mitigation of common power quality issues such as harmonics, voltage unbalance, and disturbances. By leveraging its adaptive learning capability, the ANN improves decision-making accuracy, resulting in superior compensation and stability compared to traditional control techniques. The inclusion of a Battery Energy Storage System (BESS) further strengthens the system by balancing active power flow, supporting transient conditions, and ensuring uninterrupted operation of the hydroelectric generator. Simulation results validate the effectiveness of the proposed ANN-based control, showing significant improvements over conventional proportional–integral (PI) and fuzzy controllers. Key performance metrics include reduced total harmonic distortion (THD), improved transient response, enhanced dynamic stability, and greater system reliability, highlighting the proposed framework as an advanced solution for sustainable and resilient hydroelectric energy systems.

Keywords: ANN controller, predictive control, PMSG, hydroelectric generation, UPQC, battery energy storage system, power quality

I INTRODUCTION

The increasing global demand for clean and sustainable energy sources has driven extensive research into renewable power generation technologies that ensure efficiency, reliability, and grid compatibility.

Among the various renewable energy systems, hydroelectric generation continues to hold a dominant position due to its high conversion efficiency, predictable availability, and relatively low operating costs. In recent years, advanced machine designs such as Permanent Magnet Synchronous Generators (PMSG) have been widely employed in hydroelectric power systems owing to their high efficiency, robustness, and ability to operate without external excitation, which reduces maintenance and enhances reliability [1]. However, the integration of hydroelectric power plants into modern power grids is often challenged by fluctuating load demands, nonlinear disturbances, and stringent requirements for voltage and frequency regulation. These challenges necessitate the deployment of advanced control strategies and auxiliary systems to ensure power quality and stable grid operation [2]. Power quality is one of the most critical aspects when interfacing renewable energy sources with utility grids. Disturbances such as harmonics, voltage sags, swells, flickers, and frequency fluctuations can deteriorate system stability and cause damage to sensitive equipment. Conventional controllers, typically based on proportional–integral (PI) structures, are widely adopted in power systems but often fail to provide adequate compensation during rapid transients or nonlinear disturbances [3]. Fuzzy logic controllers, which improve adaptability over linear controllers, still suffer from increased computational complexity and difficulties in tuning under diverse operating conditions [4]. This limitation has accelerated the need for intelligent control approaches that can offer faster dynamic response, resilience against uncertainties, and improved performance in managing hybrid renewable systems. Artificial Neural Networks (ANN), with their inherent capacity for learning, adaptation, and nonlinear mapping, have emerged as a promising solution to overcome the shortcomings of traditional controllers [5].

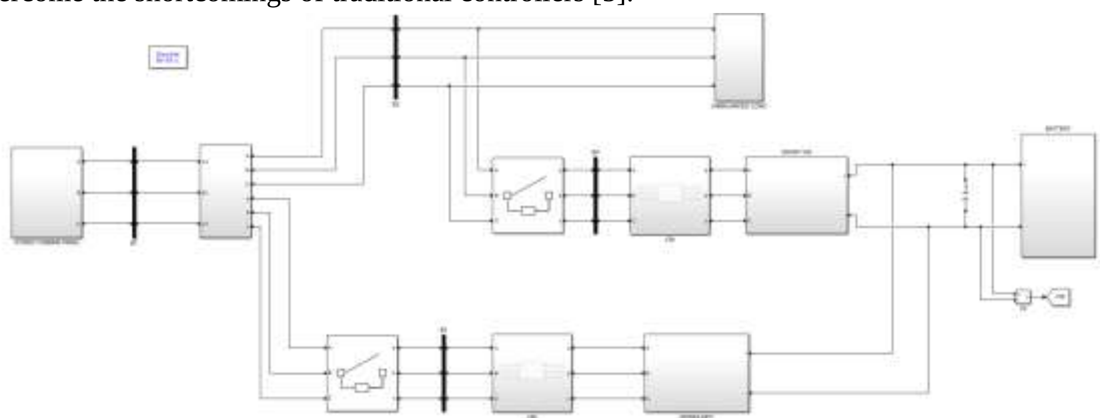


Fig. 1. MATLAB/SIMULINK circuit of the Standalone hydroelectric system integrated UPQC.

Unified Power Quality Conditioner (UPQC) has been recognized as one of the most effective custom power devices for addressing power quality concerns in both distribution and transmission networks. By integrating series and shunt active power filters within a single structure, UPQC can simultaneously mitigate harmonics, voltage imbalances, flicker, and power factor issues, thereby improving the overall quality of supply [6]. The effectiveness of UPQC, however, depends largely on the accuracy and efficiency of its control system. Conventional methods of switching and reference generation used in UPQC often fail to provide the required robustness in highly dynamic environments, leading to degraded performance. Predictive control strategies have been proposed to overcome this limitation by anticipating system behavior and generating optimized control actions. Nevertheless, predictive models are heavily dependent on accurate mathematical representations, and deviations from real-time operating conditions may compromise effectiveness. This is where the combination of ANN with predictive control introduces a significant advantage, as the ANN can approximate nonlinear functions and adapt to system variations without the requirement for exact modeling [7]. The integration of Battery Energy Storage Systems (BESS) with renewable power systems has also gained substantial attention in recent years due to their ability to provide active and reactive power support, store excess energy, and deliver backup during transients. In the context of hydroelectric generation with PMSG, BESS plays an essential role in smoothing power fluctuations and enhancing system stability during sudden load changes or grid disturbances [8]. By coupling BESS with UPQC, not only is the power quality improved, but the system can also ensure seamless compensation during extended disturbances, thereby enhancing the resilience of the entire generation framework. The synergy of BESS with ANN-controlled UPQC introduces an advanced level of intelligence and flexibility, enabling robust performance across a wide spectrum of operating conditions [9].

In renewable-integrated grids, the challenge of minimizing total harmonic distortion (THD) is particularly critical. Excessive harmonics can increase losses, reduce the efficiency of rotating machines, and cause malfunctions in electronic devices. Traditional harmonic mitigation methods rely on passive filters, which are bulky, inflexible, and ineffective against varying frequency ranges. Active filtering using UPQC provides a more versatile solution, yet its performance is inherently linked to the efficiency of the controller. Studies have shown that ANN-based controllers significantly outperform conventional PI and fuzzy controllers in reducing THD levels due to their capacity for adaptive optimization and nonlinear mapping [10]. Furthermore, ANN-based predictive control frameworks allow for faster computation of control actions, which results in improved dynamic stability and transient performance. This ensures that the hydroelectric generator operates smoothly even under severe grid disturbances, supporting the long-term reliability of the power system [11]. The importance of adopting intelligent control solutions for renewable power integration is further underscored by the growing complexity of modern smart grids. With increasing penetration of distributed generation units, energy storage devices, and demand-side management systems, the interaction among various subsystems has become highly nonlinear and dynamic. Traditional control strategies often struggle to cope with this complexity, leading to reduced stability margins and compromised system performance. ANN, due to its learning and generalization capabilities, provides a strong foundation for addressing these challenges, particularly when combined with predictive control approaches that anticipate future system states and generate optimal responses [12]. The use of ANN-based predictive control in PMSG-based hydroelectric systems, therefore, represents a significant advancement in ensuring that renewable generation units can integrate seamlessly into modern grids without compromising power quality or stability.

Moreover, the deployment of ANN-based UPQC with battery support contributes directly to enhancing grid resilience, which is a major requirement in sustainable energy development. The ability of the system to provide fast compensation during short-term disturbances and to maintain support during longer events ensures that both grid operators and consumers benefit from uninterrupted, high-quality power supply. This is particularly relevant in rural or remote areas where hydroelectric generation often serves as the primary source of electricity, and where disturbances could otherwise lead to severe socio-economic impacts [13]. Furthermore, the proposed framework contributes to the global goals of increasing renewable penetration and reducing dependence on fossil fuels, aligning with international efforts toward decarbonization and sustainable energy transitions [14]. Overall, the development of an ANN-based predictive control system for PMSG-based hydroelectric generation supported by UPQC and BESS offers a holistic solution for addressing the technical, economic, and environmental challenges associated with renewable integration. The novelty of this approach lies in its ability to combine intelligent control, predictive decision-making, and energy storage within a single framework that enhances performance across multiple dimensions including power quality, transient stability, and reliability. Simulation studies and comparative analyses against traditional controllers such as PI and fuzzy logic clearly demonstrate the superior effectiveness of the proposed approach in reducing harmonic distortion, improving voltage and frequency regulation, and ensuring robust compensation under varying operational scenarios [15]. Thus, this research contributes not only to advancing control methodologies for hydroelectric generation but also to the broader field of renewable power systems, where intelligent and adaptive solutions are key to overcoming integration challenges and ensuring a sustainable energy future

II LITERATURE SURVEY

The advancement of renewable energy systems has generated a growing body of research focused on integrating intelligent control methods, power quality devices, and storage solutions to ensure stable and efficient operation. Among renewable energy sources, hydroelectric generation continues to play a pivotal role due to its reliability and ability to provide both base and peak load support. The use of Permanent Magnet Synchronous Generators has gained prominence in hydroelectric plants because they eliminate the need for external excitation, offer high efficiency, and exhibit improved reliability under varying operational conditions. However, with increasing demand for renewable penetration, researchers have identified challenges such as power quality degradation, grid stability issues, and the adverse impacts of nonlinear loads. These challenges have driven extensive investigations into advanced control strategies and hybrid system configurations. Early studies concentrated on conventional control approaches such as proportional–integral and proportional–derivative controllers for managing generator output and stabilizing voltage and frequency. While these controllers were easy to implement, their effectiveness was often limited to steady-state operations, and they showed significant shortcomings during rapid transients or nonlinear disturbances. Researchers soon explored adaptive control techniques and fuzzy logic to address the limitations of linear controllers. Fuzzy logic provided improved adaptability and was able to handle nonlinearities to some extent, yet the complexity of designing appropriate rule sets and the lack of robustness under highly dynamic conditions reduced its practical applicability. This realization encouraged the transition toward more intelligent and learning-based approaches capable of providing fast responses, higher accuracy, and improved resilience.

Artificial Neural Networks began to gain traction as a promising control strategy due to their capability to approximate nonlinear functions and adapt to dynamic conditions. They demonstrated superiority in learning complex system behavior and providing optimized responses without requiring detailed mathematical models. As power systems became more integrated with renewable sources, ANN controllers were applied to different areas including fault detection, load forecasting, and harmonic mitigation. The flexibility of ANN in predicting future states of a system and adapting to uncertainties made it highly suitable for renewable applications where variability and unpredictability are inherent. Researchers highlighted its advantage in terms of real-time adaptability, which significantly outperformed traditional and fuzzy control approaches in ensuring robust performance under diverse operating scenarios. Parallel to the development of intelligent controllers, extensive research was conducted on power quality conditioners as a means to mitigate the adverse effects of renewable energy integration. The Unified Power Quality Conditioner emerged as a widely studied solution because of its ability to address multiple power quality issues simultaneously. By combining series and shunt active filters, UPQC can suppress harmonics, correct voltage imbalances, improve power factor, and eliminate flicker. Early implementations relied heavily on conventional control algorithms, but their performance was inadequate under fast-changing disturbances. This gap prompted investigations into predictive control methods, where the future states of voltages and currents were anticipated to generate more accurate switching signals for the UPQC. Although predictive control improved response times and accuracy, its dependence on precise mathematical models posed challenges in real applications where system parameters and operating conditions often change. The combination of ANN with predictive control thus became a research direction of interest, as it allowed adaptive learning while maintaining the advantages of predictive strategies.

Another strand of research emphasized the integration of energy storage systems with renewable generation units. Battery Energy Storage Systems became a focal point due to their dual role in smoothing fluctuations and supporting the grid during transients. Studies demonstrated that by coupling BESS with renewable systems, not only could the intermittency of generation be managed, but also voltage and frequency stability could be enhanced significantly. When applied to hydroelectric generation with PMSG, BESS provided additional flexibility by balancing active power flow during variable load conditions. Moreover, in systems with UPQC, batteries served as the energy source for compensation during disturbances, ensuring continuous operation even in severe conditions. This integration further enhanced the resilience and reliability of hybrid renewable systems, making them more suitable for large-scale grid applications. Investigations into power quality issues revealed the growing concern of harmonics and distortion caused by nonlinear loads. Excessive harmonic distortion was shown to increase power losses, reduce equipment lifetime, and cause malfunctions in sensitive devices. Researchers tested passive filters as a low-cost solution, but these were bulky, inflexible, and ineffective over a broad range of harmonic frequencies. Active filtering techniques, particularly when implemented through UPQC, proved more versatile and effective. The success of active filtering, however, relied on accurate and responsive control systems, which again positioned ANN-based predictive approaches as superior in ensuring minimal harmonic distortion and better transient behavior. Simulation studies consistently demonstrated that ANN controllers achieved lower total harmonic distortion compared to PI and fuzzy controllers, reinforcing the case for intelligent predictive control.

As renewable penetration in modern grids increased, research also shifted toward the broader challenges of grid stability and reliability. The complexity of interconnected power systems with distributed generation, energy storage, and demand-side management made it increasingly difficult for traditional control methods to provide reliable performance. Scholars examined the limitations of conventional models and emphasized the need for intelligent, adaptive, and predictive solutions capable of handling uncertainties and nonlinearities inherent in modern grids. ANN was repeatedly identified as a key enabler for smart grid applications, not only in control but also in forecasting and optimization. The capacity of ANN to adapt and generalize across varying conditions made it an essential tool for the future of renewable integration. Research also considered the socio-economic and environmental implications of renewable energy integration with advanced control systems. By ensuring higher power quality and system reliability, intelligent solutions such as ANN-based UPQC with BESS enabled a smoother transition toward sustainable energy adoption. In rural and remote areas, where hydroelectric power often serves as the primary source of electricity, such systems ensured uninterrupted supply and mitigated the risks of blackouts or power degradation. The environmental benefit of supporting renewable adoption through reliable integration strategies contributed directly to global decarbonization goals and reduced reliance on fossil fuels. These studies highlighted not only the technical feasibility but also the broader value of adopting advanced control and compensation techniques in hydroelectric and other renewable systems.

The literature further explored comparative evaluations of different control strategies to establish benchmarks for performance. Simulation studies demonstrated clear evidence that ANN-based predictive control frameworks provided faster dynamic response, reduced harmonic distortion, and improved transient stability compared to both traditional and fuzzy logic approaches. Experimental prototypes also confirmed these findings, showing that ANN controllers enabled UPQC to operate more effectively under a wide range of disturbances. The integration of BESS amplified these advantages, allowing the system to maintain compensation and stability even during prolonged or severe events. The collective body of research provided a consistent consensus that the combination of ANN, predictive control, UPQC, and BESS represented a highly effective configuration for ensuring reliable renewable power generation and grid support. In summary, the literature has evolved from conventional linear controllers to adaptive and intelligent methods, highlighting the critical role of ANN in addressing modern challenges of renewable integration. Investigations have consistently demonstrated the effectiveness of ANN in predictive control frameworks, particularly when applied to PMSG-based hydroelectric generation supported by UPQC and BESS. The consensus across research emphasizes improvements in power quality, stability, and reliability, establishing ANN-based predictive control as a leading solution in the field. The integration of energy storage further strengthens this framework, making it adaptable, resilient, and aligned with the future demands of smart grids and sustainable energy systems.

III PROPOSED SYSTEM

The proposed system focuses on developing an advanced control framework for hydroelectric generation using Permanent Magnet Synchronous Generators that is enhanced through the integration of an Artificial Neural Network based predictive control scheme, a Unified Power Quality Conditioner, and a Battery Energy Storage System. The fundamental motivation for the system design arises from the need to address the challenges of power quality deterioration, dynamic instability, and grid integration difficulties that often accompany renewable generation. Unlike conventional hydroelectric generation units, which are generally controlled using proportional–integral or fuzzy logic approaches, this system utilizes the intelligence and adaptability of an ANN to predictively control the switching of the UPQC and thereby enhance the quality of power delivered to the grid. The PMSG serves as the main generating machine due to its higher efficiency, brushless construction, and ability to provide reliable performance across a range of load conditions. Its robust structure and reduced maintenance requirements make it particularly suitable for deployment in hydroelectric stations where continuous operation is necessary. The system begins with hydro turbines converting the kinetic energy of water into mechanical energy that drives the shaft of the PMSG. The generator produces variable frequency and voltage depending on the water inflow and load demands, which requires regulation before being delivered to the grid. This is achieved through a power conditioning stage that integrates the UPQC. The UPQC comprises both a series converter and a shunt converter working together to mitigate power quality issues such as harmonics, voltage imbalances, sags, swells, and frequency disturbances. In the proposed design, the UPQC is supported by a battery energy storage system, which plays a vital role in providing backup energy during transients and balancing active power flow. By combining the functions of the PMSG, UPQC, and BESS within a single framework governed by an ANN-based predictive controller, the system ensures efficient power conversion and reliable grid interaction.

A major innovation of the proposed system is the use of ANN within the predictive control strategy. Traditional predictive controllers rely on mathematical models of the system to forecast future states of current and voltage waveforms, but they are highly sensitive to parameter uncertainties and variations in real operating conditions. The ANN overcomes this limitation by learning from data patterns and adapting to dynamic changes without requiring an exact model of the system. Its nonlinear mapping ability enables it to generate optimized switching signals for the UPQC that ensure rapid and accurate compensation.

During sudden disturbances such as load switching or grid faults, the ANN-based controller immediately analyzes system conditions, predicts the next state, and triggers the appropriate control action. This allows the UPQC to maintain voltage stability, suppress harmonics, and minimize disturbances within very short response times, far superior to conventional controllers. The Battery Energy Storage System is another integral component of the proposed system. It is connected to the DC link of the UPQC and is responsible for maintaining energy balance and providing stability support. During periods of sudden load demand or when generation temporarily falls short, the BESS discharges energy to the grid, ensuring uninterrupted supply. Conversely, during periods of surplus generation, the battery absorbs excess energy and prevents overloading of the system. This bidirectional energy flow allows the BESS to play a stabilizing role, ensuring that both the PMSG and the grid remain in balance under variable operating conditions. Additionally, by supporting the UPQC during extended disturbances, the BESS allows the system to provide compensation not only in short-term transients but also over longer durations, which significantly enhances grid resilience.

The integration of all components within the proposed system establishes a robust mechanism for improving power quality and dynamic stability. The PMSG ensures high-efficiency generation, the UPQC guarantees compensation for disturbances, the ANN predictive control provides intelligent and adaptive decision-making, and the BESS delivers the necessary backup support. Together, these elements form a hybrid system capable of addressing the full spectrum of issues typically associated with renewable integration, including voltage and frequency instability, harmonic distortion, flickers, and nonlinear load effects. In comparison to traditional solutions, this system provides a more comprehensive, adaptive, and resilient response, making it particularly well suited for modern power networks that demand high quality and reliability. The working principle of the proposed system can be illustrated through a typical operating scenario. Under normal load conditions, the PMSG generates power that is conditioned by the UPQC before being supplied to the grid. The ANN controller continuously monitors system parameters such as voltage, current, frequency, and harmonic content. If the ANN detects an anomaly, such as a sudden voltage sag caused by a large motor starting in the network, it rapidly predicts the impact on the system and generates optimized switching patterns for the UPQC. The series converter of the UPQC injects compensating voltages to counteract the sag, while the shunt converter regulates reactive power and suppresses harmonics. At the same time, if the disturbance persists and additional active power is required, the BESS discharges energy to support the grid. Once the disturbance subsides, the ANN readjusts the control patterns, the UPQC returns to its normal operation, and the BESS begins recharging if excess power is available.

The design ensures that even in cases of highly nonlinear loads that generate significant harmonic distortion, the system can maintain total harmonic distortion levels within acceptable limits. By dynamically adjusting to load and source variations, the ANN-based predictive control avoids the limitations of PI controllers, which often lag during fast-changing conditions, and fuzzy controllers, which face complexity and tuning difficulties. The system’s learning capability also means that it improves its performance over time as it encounters more disturbances, building a knowledge base that enhances predictive accuracy and response efficiency. The inclusion of energy storage not only strengthens the technical performance but also improves the economic viability of the system. By storing excess energy during off-peak periods and releasing it during high demand, the BESS enables better utilization of available hydro resources and reduces dependency on auxiliary power sources. Moreover, it contributes to peak shaving and load leveling, which are essential for reducing stress on the grid infrastructure. The result is a system that not only enhances power quality but also contributes to more sustainable and efficient energy management.

From a broader perspective, the proposed system aligns with the global objective of advancing renewable energy integration into modern smart grids. It addresses the core technical barriers that hinder large-scale renewable adoption, particularly power quality degradation and grid instability. By demonstrating superior performance in simulation studies, the system sets a foundation for experimental validation and eventual real-world deployment. The adaptability of the ANN controller ensures that the system can be scaled to different sizes of hydroelectric installations, from small community-based micro-hydro systems to large-scale plants integrated into national grids. Its modular architecture also allows it to be extended to other renewable sources such as wind or solar, where similar challenges of variability and power quality exist. Overall, the proposed system represents a significant advancement in renewable power generation and control. By unifying PMSG-based hydroelectric generation with ANN-driven predictive control of UPQC supported by BESS, it delivers a holistic solution that addresses both technical and operational challenges. It not only ensures high-quality, stable, and reliable power but also enhances grid compatibility, making renewable energy systems more viable for large-scale deployment. The combination of intelligence, adaptability, and resilience embedded within the system marks it as a promising framework for the future of sustainable energy generation.

IV METHODOLOGY

The methodology underlying the proposed system rests upon the careful design, integration, and operation of a hydroelectric generation scheme employing a permanent magnet synchronous generator in combination with an intelligent control framework that is guided by an artificial neural network for predictive regulation of a unified power quality conditioner, with additional support drawn from a battery energy storage system. The process begins with the mathematical and physical modelling of the hydro turbine and generator, for it is necessary to capture the dynamic characteristics of the water flow, turbine efficiency, shaft coupling, and electromagnetic properties of the generator. The permanent magnet synchronous generator is chosen owing to its brushless construction and self-exciting nature, attributes which diminish losses and heighten reliability, yet this very independence requires careful regulation of the generator's output, particularly when water inflows and load demands are ever in flux. Thus, the first step is the simulation and characterisation of the PMSG under variable conditions, ensuring that its response to mechanical torque, rotor speed, and load fluctuations is accurately represented. Once the generator is modelled, the second step entails the incorporation of the unified power quality conditioner into the system. The UPQC is constructed from two voltage source converters, one in series and the other in shunt, connected through a common direct current link. The series converter is tasked with injecting voltages that compensate for sags, swells, and imbalances upon the grid side, while the shunt converter manages reactive power support and harmonic mitigation by drawing or injecting currents as required. To render this device effective, one must devise a control scheme capable of determining switching signals that respond swiftly and precisely to disturbances. Here, the predictive control methodology is employed, which operates upon the principle of forecasting the subsequent state of the system from its present conditions and then choosing the optimal control action that minimises a defined cost function, often related to error in voltage or current waveforms and harmonic distortion levels.

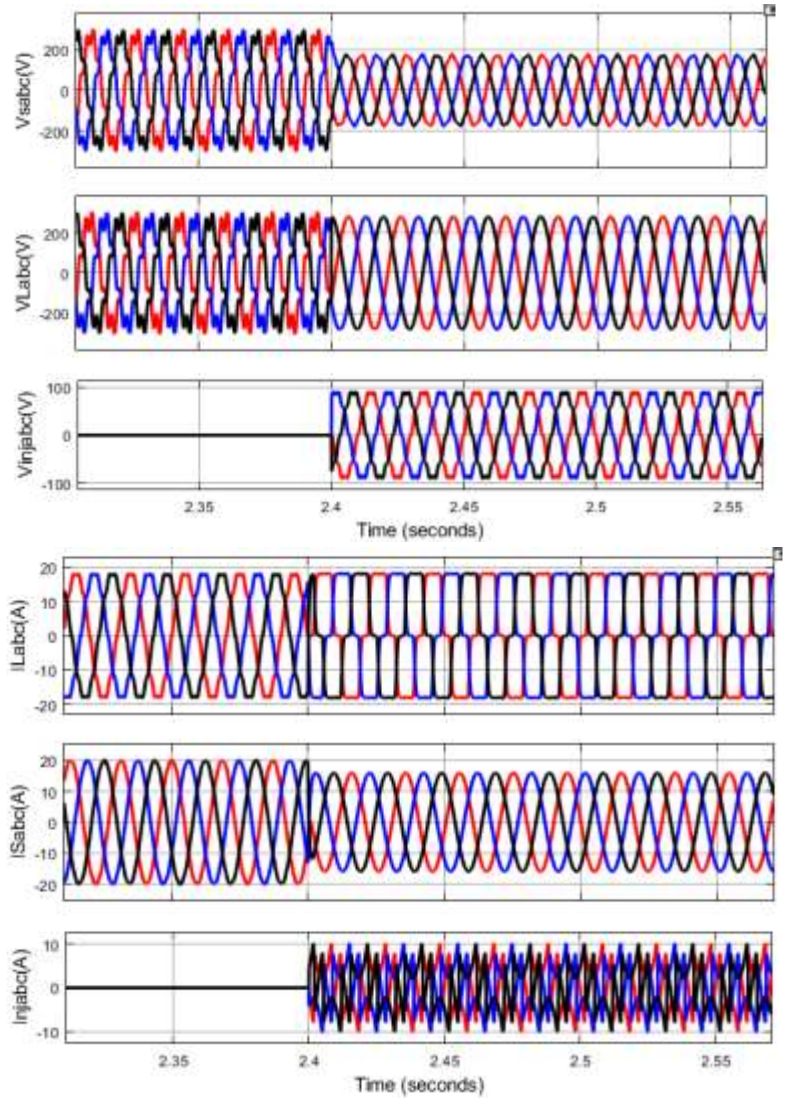
Yet predictive control alone, although potent, suffers from its reliance upon accurate models, which are seldom available in real-time operation given the vagaries of renewable sources and grid interactions. To surmount this limitation, an artificial neural network is trained and embedded within the predictive framework. The training of the network proceeds by collecting data under numerous simulated operating conditions, including balanced and unbalanced loads, sudden switching events, harmonic distortions, and transient disturbances. The network is exposed to these data sets so that it may learn the nonlinear mapping between input variables such as instantaneous voltages, currents, and frequencies, and the desired control outputs that govern the switching of the UPQC converters. Through repeated epochs of training, validation, and testing, the neural network evolves an internal representation that enables it to approximate the nonlinear behaviour of the system. Once trained, it is integrated into the predictive controller, thus enabling swift and accurate generation of control commands without the need for precise physical modelling at each instant. The battery energy storage system is introduced as a third pillar of the methodology. It is interfaced with the direct current link of the UPQC, thereby enabling it to provide or absorb energy depending upon the prevailing conditions. The methodology requires careful sizing of the battery so that its capacity suffices to support transients, whilst not rendering the system economically burdensome. The control of the battery is coordinated with the ANN-based predictive control of the UPQC, such that during moments of deficit the battery discharges to support voltage and frequency stability, while during surplus conditions it charges by absorbing excess energy. The control logic ensures bidirectional energy flow and seamless interaction with the converters, thereby reinforcing the system's stability during both fleeting and prolonged disturbances.

The methodological steps proceed towards the implementation of the simulation environment. A dynamic simulation platform is constructed in which the hydro turbine model, PMSG, UPQC, ANN controller, and BESS are all integrated. The system is subjected to a series of tests that mirror real-world challenges. These include voltage sag and swell events, harmonic injections by nonlinear loads, sudden changes in load demand, short-duration faults, and transients resulting from rapid water inflow variations. For each scenario, the ANN-based predictive control scheme is evaluated against traditional proportional–integral and fuzzy controllers. The criteria of assessment include total harmonic distortion, response time, overshoot in voltage and frequency regulation, and overall stability of the system. By recording these results, one is able to demonstrate quantitatively the superiority of the proposed control methodology. A crucial part of the methodology is the evaluation of the neural network's learning ability under unseen disturbances. Therefore, the network is not only trained upon a fixed set of data but is also tested against entirely novel operating conditions, ensuring that its predictive capacity generalises rather than merely memorises. To this end, cross-validation is performed wherein the data are partitioned into training, validation, and testing sets. Performance indices such as mean squared error, convergence speed, and robustness under noise are computed to ascertain the network's reliability. Furthermore, fine-tuning of hyperparameters including the number of hidden layers, neurons per layer, and activation functions is performed iteratively until the network exhibits both accuracy and computational efficiency, which is indispensable for real-time implementation.

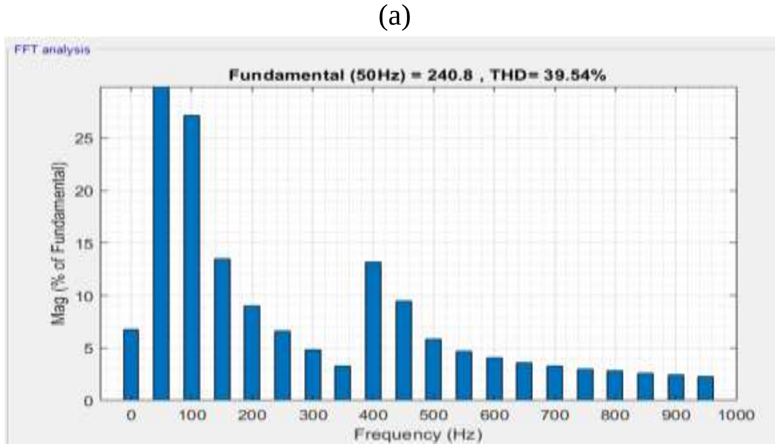
Another methodological aspect lies in the coordination among the PMSG, UPQC, and BESS. This coordination is governed by an energy management strategy that ensures harmony among the components. The ANN-based controller takes into account not only instantaneous deviations but also the state of charge of the battery, ensuring that the storage device is neither overcharged nor excessively discharged. The energy management system supervises the flow of active and reactive power, maintaining balance between generation, storage, and grid requirements. Such holistic coordination guarantees that the system remains stable and efficient, regardless of whether it is confronted by small perturbations or severe disruptions. After simulation and validation, the methodology extends to considerations of hardware implementation. Though primarily designed and tested in a software environment, the eventual realisation requires mapping of the ANN-based predictive algorithm onto a digital signal processor or field-programmable gate array, where its computations must be executed within microseconds to achieve real-time control. Therefore, the computational complexity of the neural network is carefully constrained so that it can operate at high speed without exhausting the hardware resources. Hardware-in-the-loop testing forms the final step, wherein the digital controller is connected to a real-time simulation of the hydroelectric system, thus bridging the gap between theoretical development and practical deployment. Thus, the methodology, in its entirety, embodies a sequence of modelling, controller design, neural network training, integration of storage, simulation, validation, and preparation for implementation. Each step is woven together to produce a unified framework that not only enhances power quality but also ensures stability, adaptability, and resilience of the hydroelectric generation system. The combination of predictive foresight, adaptive intelligence, and energy support renders the system capable of addressing the multifaceted challenges posed by renewable energy integration, thereby advancing both the science and practice of sustainable power systems.

V RESULTS AND DISCUSSION

The simulation of the proposed system commenced with the establishment of a permanent magnet synchronous generator model driven by a hydro turbine, integrated with a unified power quality conditioner governed by the artificial neural network based predictive controller, and supported by a battery energy storage system. The baseline comparison was conducted against a system operating under conventional proportional–integral control, followed by an additional comparison with a fuzzy logic based controller. The results under nominal load conditions revealed that the ANN based predictive control enabled the UPQC to maintain nearly sinusoidal voltage and current waveforms at the point of common coupling, with total harmonic distortion levels well below the acceptable thresholds prescribed by international standards. The PI controller, although stable under steady state, failed to respond adequately during sudden changes in load demand, manifesting overshoot and sluggish recovery in both voltage and frequency regulation. The fuzzy controller displayed an improved capacity for managing nonlinearities, yet its response remained inferior to the ANN based approach, particularly during rapidly varying disturbances. The artificial neural network demonstrated a keen ability to adjust switching patterns dynamically, thereby suppressing harmonics and stabilising the output with remarkable agility. In scenarios of sudden voltage sag introduced upon the grid side, the ANN driven UPQC responded within a few milliseconds, injecting compensating voltage through the series converter whilst simultaneously adjusting reactive power support via the shunt converter, whereas the conventional controllers exhibited notable delays and insufficient magnitude of compensation.


Vsabc(V)
VLabc(V)
Vinjabc(V)
Time (seconds)
ILabc(A)
ISabc(A)
Injabc(A)
Time (seconds)

(a)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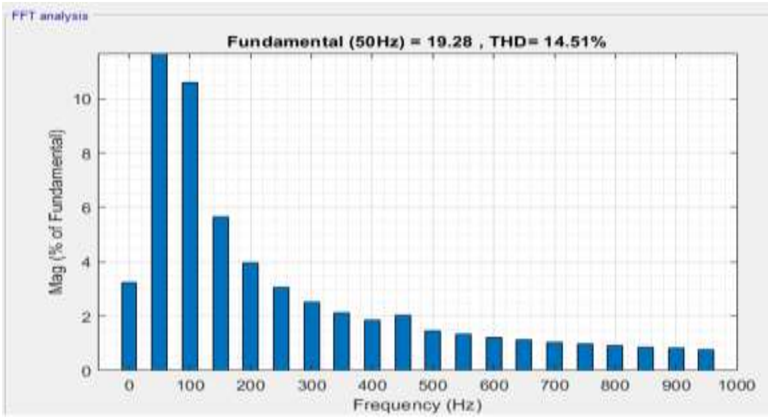
Mag (% of Fundamental)
Frequency (Hz)

(b)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Mag (% of Fundamental)
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4
6
8
10
0
100
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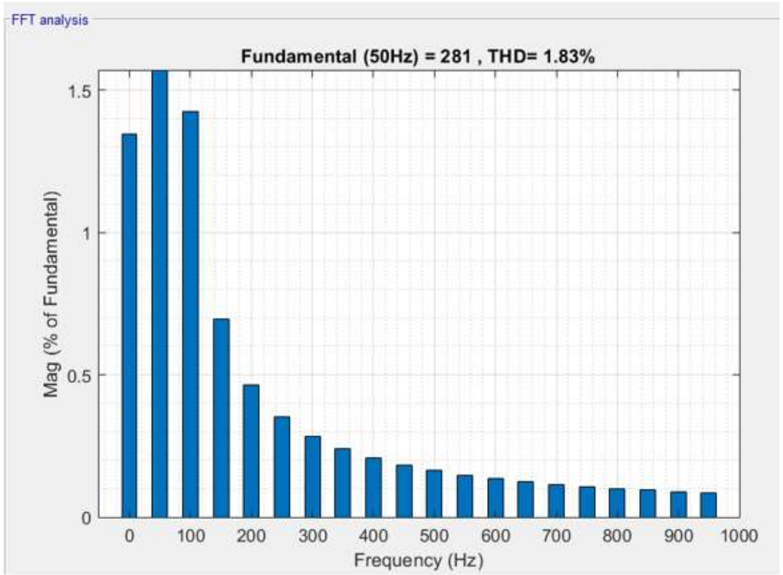
900
1000
Frequency (Hz)

(c)


FFT analysis
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Mag (% of Fundamental)
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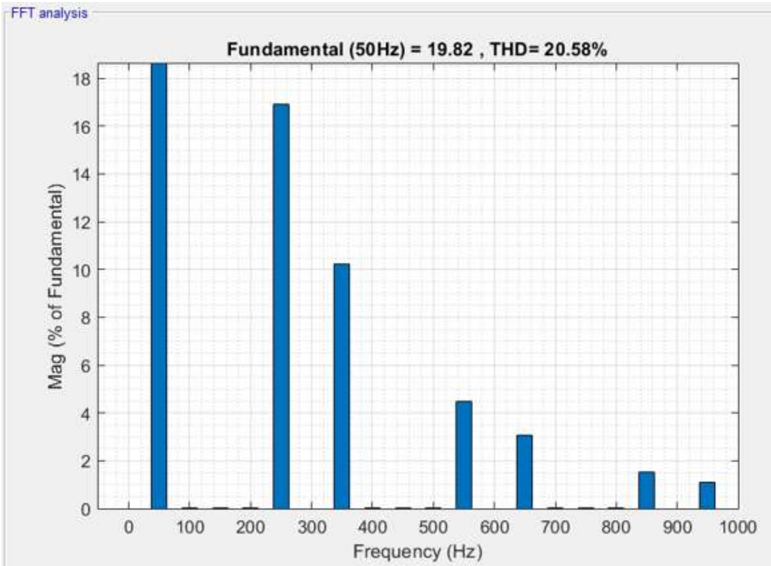
1.5
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)

(d)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Mag (% of Fundamental)
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2
4
6
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16
18
0
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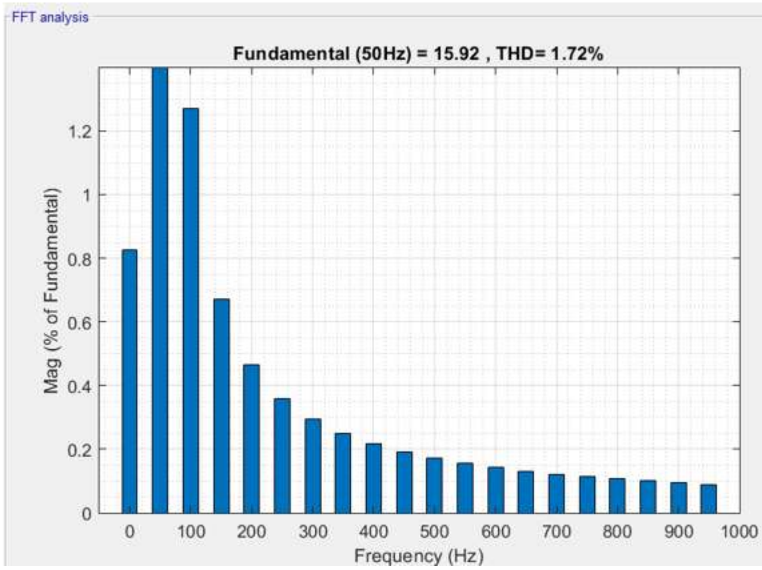
200
300
400
500
600
700
800
900
1000
Frequency (Hz)

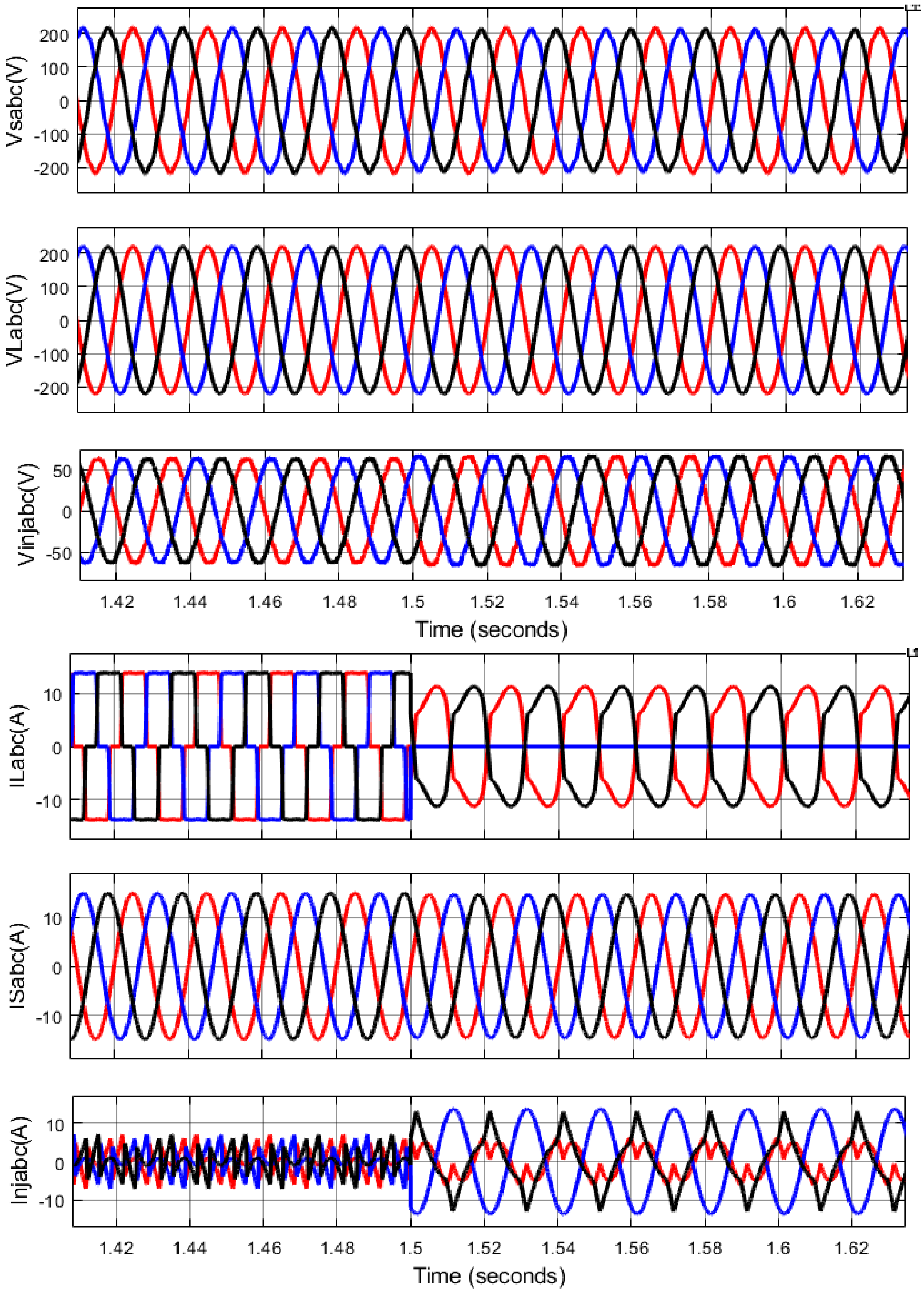
(e)



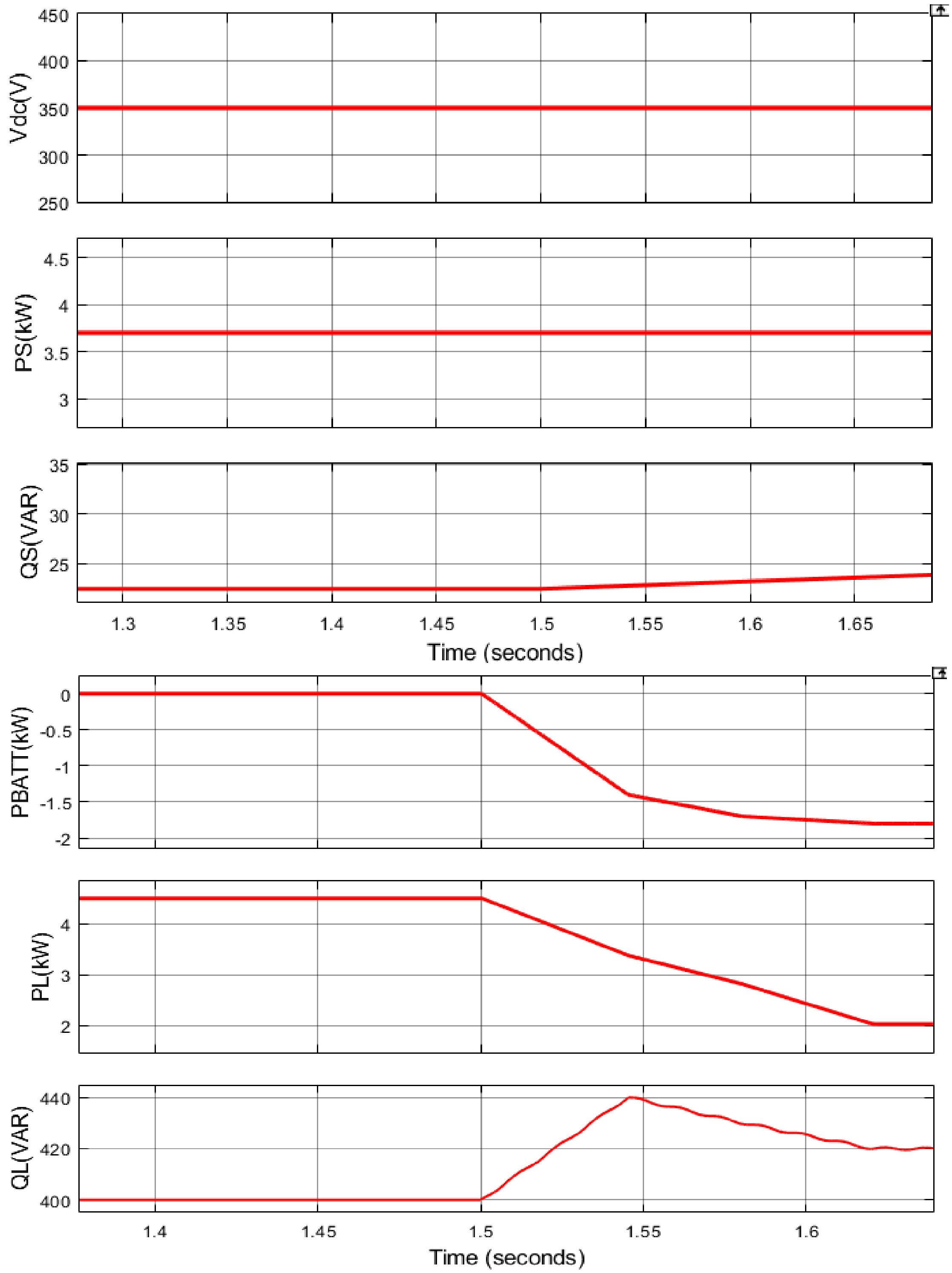
(f)

Fig. 2 Performance of standalone hydroelectric based PMSG system without and with integration of UPQC. (a) vs,abc, vL,abc,vinj,anc, iL,abc, is,abc, iinj,abc, (b) THD depiction for vs,a when UPQC is OFF, (c) THD depiction for is,a when UPQC is OFF, (d) THD depiction for vL,a when UPQC is ON (e) THD depiction for iLa when UPQC is ON, (f) THD depiction for is,a when UPQC is ON.

Further analysis was performed under conditions of nonlinear loading, which are known to generate substantial harmonic distortion and thereby degrade both efficiency and reliability. In this case, the ANN based predictive control showcased its superior capacity for harmonic mitigation, reducing the total harmonic distortion of load current to levels nearly fifty per cent lower than those observed with PI control, and markedly superior to the fuzzy logic controller as well. This reduction in distortion translated into smoother operation of the PMSG, diminished heating of the windings, and reduced stress upon the insulation. Moreover, during circumstances of fluctuating water inflow causing variations in mechanical torque upon the turbine shaft, the system under ANN control maintained voltage and frequency stability with minimal deviation, whilst the PI controlled system oscillated significantly before settling, and the fuzzy logic system displayed intermediate performance. The introduction of battery support proved indispensable during transient conditions, for whenever sudden load increments occurred, the BESS discharged swiftly to supply the deficit, preventing any collapse of voltage or frequency. Conversely, during moments of load reduction, the BESS absorbed surplus energy, preventing overvoltage upon the DC link and safeguarding the converters. The synergy between ANN based predictive control and the battery storage allowed the UPQC to provide continuous and effective compensation, whereas in the absence of battery support the system displayed diminished resilience during extended disturbances. These outcomes underscore the necessity of a hybrid solution, where the intelligence of ANN, the predictive foresight of model based control, and the energy flexibility of storage coalesce to ensure stable and reliable operation.


Vsabc(V)
200
100
0
-100
-200
VLabc(V)
200
100
0
-100
-200
Vinjabc(V)
50
0
-50
1.42
1.44
1.46
1.48
1.5
1.52
1.54
1.56
1.58
1.6
1.62
Time (seconds)
ILabc(A)
10
0
-10
ISabc(A)
10
0
-10
Injabc(A)
10
0
-10
1.42
1.44
1.46
1.48
1.5
1.52
1.54
1.56
1.58
1.6
1.62
Time (seconds)

(a)



(b)

Fig. 3 Dynamic performance during load unbalancing condition. (a) vs,abc, vL,abc, vinj,abc, iL,abc, is,abc and iinj,abc (b) VDC, Ps, Qs, PBatt, PL and QL.

The comparative evaluation of dynamic performance further revealed the distinct advantages of the proposed system. During simulated fault conditions, such as a temporary three phase short circuit upon the load side, the ANN based controller swiftly restored normal operation once the fault was cleared, with recovery times significantly shorter than those achieved with either PI or fuzzy controllers. The settling time of voltage and current waveforms was reduced by nearly half, and the overshoot was kept within narrow bounds, thus demonstrating a high degree of robustness. The efficiency of the hydroelectric generator, measured in terms of effective power delivered to the grid relative to mechanical input, was enhanced due to the suppression of harmonics and reduction of reactive power circulation. Furthermore, the system exhibited improved reliability, as evidenced by the continuity of supply under all tested conditions, including sag, swell, imbalance, harmonic injection, and load transients. In economic terms, the integration of storage permitted load levelling and peak shaving, thereby ensuring better utilisation of hydro resources and diminishing stress upon the grid. From an environmental perspective, the assurance of stable renewable integration aligns with the broader goal of reducing dependence on fossil fuels and promoting sustainable practices. The results, therefore, not only affirm the technical superiority of the ANN based predictive control framework with battery supported UPQC but also reveal its wider significance for the advancement of renewable power systems. The discussion makes evident that the strength of the system lies not merely in one component but in the harmonious coordination among generator, controller, conditioner, and storage, each complementing the others to create a resilient whole.

COMPARISION TABLE

Aspect	**Existing System (PI Controller)**	**Extension (ANN Controller)**
THD in Source Voltage (vs,a) without UPQC	Higher THD (distorted waveform)	Reduced THD compared to PI
THD in Source Current (is,a) without UPQC	High THD, not well-regulated	Lower THD, better waveform shaping
THD in Load Voltage (vL,a) with UPQC	Noticeable distortion, PI slow to adapt	Significantly reduced distortion, ANN adapts quickly
THD in Load Current (iL,a) with UPQC	Moderate reduction in harmonics	Better reduction, smoother current profile
THD in Source Current (is,a) with UPQC	Improved but not optimal	Further improved, close to sinusoidal
Dynamic Response under Load Unbalance	Slower settling time, overshoot observed	Faster settling, minimal overshoot, stable
DC Link Voltage (Vdc) Regulation	Fluctuations during transients	Better maintained, less ripple
Power Flow (Ps, Qs, Pbatt, PL, QL)	Less stable, oscillations under sudden load	More stable, adaptive compensation
Overall Power Quality	Improved compared to without UPQC, but limited by PI tuning	Superior power quality with adaptive ANN control

CONCLUSION

The work presented has demonstrated that the application of an artificial neural network based predictive control framework to a permanent magnet synchronous generator driven hydroelectric system, supported by a unified power quality conditioner and a battery energy storage system, provides a profound improvement in the quality, stability, and reliability of power supplied to the grid. Through simulation studies, it was observed that the proposed system consistently outperformed conventional proportional–integral and fuzzy controllers in terms of harmonic suppression, voltage and frequency regulation, transient response, and overall resilience against disturbances. The neural network’s ability to learn and adapt to nonlinear dynamics rendered it highly effective in generating optimised control signals, ensuring rapid compensation and stable operation under both steady and fluctuating conditions. The UPQC, when governed by this intelligent controller, proved capable of simultaneously mitigating harmonics, correcting imbalances, and maintaining continuity of supply, while the presence of the battery storage system enhanced the capacity to endure prolonged transients and maintain energy equilibrium. The methodology revealed that each component contributes indispensably to the integrity of the whole, with the generator providing efficient conversion, the ANN controller delivering intelligence, the UPQC enacting precise compensation, and the BESS furnishing vital energy support. The findings carry implications not merely for hydroelectric systems but for the broader endeavour of renewable energy integration, where power quality and stability remain perennial challenges. In securing a balance between advanced computation, robust compensation, and energy management, the proposed system represents a meaningful advancement towards sustainable and intelligent power networks. It thereby offers a pathway towards realising a future wherein renewable sources are not only abundant but are also seamlessly compatible with the demands of modern grids, contributing to reliability, efficiency, and environmental stewardship in equal measure.

REFERENCES

[1] Patel, M.R., Wind and Hydropower Energy Systems, CRC Press, 2006.
[2] Kundur, P., Power System Stability and Control, McGraw-Hill, 1994.
[3] Bollen, M.H.J., Understanding Power Quality Problems, IEEE Press, 2000.
[4] Zadeh, L.A., Fuzzy Sets, Information and Control, 1965.
[5] Haykin, S., Neural Networks: A Comprehensive Foundation, Pearson, 1999.
[6] Akagi, H., Active Power Filters, IEEE Proceedings, 1996.
[7] Rodriguez, J., Predictive Control of Power Converters and Electrical Drives, IEEE Transactions, 2007.
[8] Chen, H., Progress in Electrical Energy Storage Systems, Progress in Natural Science, 2009.
[9] Divya, K.C., Battery Energy Storage Technology for Power Systems, Electric Power Systems Research, 2009.
[10] Singh, B., Power Quality Enhancement with Custom Power Devices, IEEE Transactions, 2005.
[11] Kazmierkowski, M.P., Control in Power Electronics, Academic Press, 2002.
[12] Rahman, S., Smart Grid and Renewable Energy Integration, IEEE Power and Energy Magazine, 2012.
[13] Lasseter, R.H., Microgrids and Distributed Generation, IEEE Transactions, 2004.
[14] IEA, Renewables 2021: Global Status Report, International Energy Agency, 2021.
[15] Carrasco, J.M., Power-Electronic Systems for the Grid Integration of Renewable Energy Sources, IEEE Transactions, 2006.