A Modified Unified Power Quality Conditioner (UPQC) Approach for Improving Power Quality in Smart Grids

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ABSTRACT

A growing number of renewable energy sources, including wind and solar photovoltaic (PV) energy, are being integrated into intelligent networks, which has led to concerns about power quality (PQ). Voltage drops, harmonics, and imbalanced situations caused by these intermittent and variable sources hurt grid reliability and load performance. To overcome these obstacles, this study proposes a Modified Unified Power Quality Conditioner (M-UPQC) that integrates PV and wind energy systems and is equipped with a Fuzzy Logic Controller (FLC). The M-UPQC is designed to reduce voltage disturbances and harmonics in the system through the simultaneous operation of series and shunt active power filters. In response to changes in voltage and current measured in real time, the fuzzy logic controller adaptively modifies control signals, making the system more responsive and dynamic. Greater speed and accuracy in compensating are made possible by this intelligent control method compared to traditional PI controllers. Supporting both active and reactive power demands, the proposed architecture also enables the coordinated operation of renewable sources, thereby reducing their impact on the grid. The system's functionality is tested in MATLAB/Simulink simulations when renewable power sources experience intermittency and voltage sag, as well as harmonic injection. The results show that the M-UPQC successfully maintains the

load voltage at nominal levels during voltage sag events. The FFT spectrum confirms that prominent harmonic components have been suppressed. Finally, a complete solution for smart grid power quality enhancement may be achieved by integrating a fuzzy-controlled M-UPQC with PV and wind sources. The proposed system enhances both the efficiency and reliability of distributed renewable energy sources, while also mitigating voltage fluctuations and harmonic distortion. For that reason, it will be an excellent addition to innovative and sustainable power networks of the future.

I. INTRODUCTION

Without a doubt, power-electronics devices have resulted in significant advancements in technology. Power quality issues are not new, but they have become more widespread due to the increasing prevalence of power electronics-driven loads in industrial settings. Power electronics loads, on the other hand, are the most common source of distribution system aberrant harmonic currents and often need a perfect sinusoidal supply voltage for proper operation. Over the years, gadgets have been created that can overcome these shortcomings in this case. A flexible compensator, the universal power quality conditioner (UPQC), and the static synchronous compensator (STATCOM) are part of the solution set.

Two active filters, one in series and one in shunt arrangement, are linked back-to-back in the power circuit of a UPQC. In this setup, both the supply voltage and the load current can be adjusted simultaneously, resulting in a balanced and sinusoidal current drawn from the grid and supplied to the load. At the fundamental frequency, the shunt active filter acts as an AC voltage source, and the series one as an AC source; this is the dual topology of the UPQC. Here, optimising the power converters' LCL filters and designing superior control gains come together to enhance the compensator's overall performance significantly.

Transmission networks have extensively utilised STATCOMs for voltage regulation through dynamic reactive power compensation. Voltage control is where the STATCOM excels these days, with the UPQC serving as a solution for more specialised applications. In addition, the usage of these latter ones is limited to specific scenarios when the benefits of improved power quality outweigh the relatively high prices, rendering traditional alternatives impractical. Expanding the

UPQC device's capability to include a STATCOM opens up new possibilities for its use, such as serving as a coupling device in grid-tied microgrids and as a component in smart grids with dispersed generation. When functioning as UPQCs, the modified UPQC and the original UPQC were compared in terms of their performance. What distinguishes series power converters from shunt power converters is the type of source that each of these compensators attempts to mimic. The UPQC method involves tuning the series converter to produce a non-sinusoidal voltage and the shunt converter to produce a non-sinusoidal current. Then, in

The UPQC controller must precisely calculate and synthesise the harmonic voltage and current that need to be corrected in real-time. In contrast, iUPQC uses a shunt converter to provide a controlled sinusoidal voltage and a series converter to provide a controlled sinusoidal current.

Since harmonic voltages occur naturally across the series current source and harmonic currents flow naturally into the shunt voltage source, determining the harmonic voltage and current to be corrected is not essential. Real power converters have a limited power rate capability that decreases with increasing switching frequency. Since the compensating references of the enhanced UPQC are pure sinusoidal waveforms at the fundamental frequency, it follows that in the event of high-power applications, the improved UPQC provides superior solutions than the UPQC. Due to its increased switching frequency, the UPQC also experiences greater switching losses.

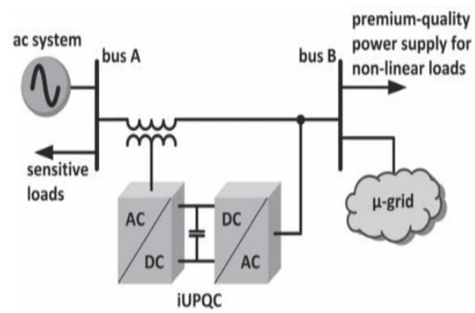

Fig. 1.1. Example of the applicability of improved **UPQC.**

To maximise the benefits of the enhanced UPQC capabilities, this study proposes a new controller. In addition to regulating the voltage on the load-side bus, this updated UPQC controller now also regulates the voltage on the grid-side bus, functioning as a STATCOM for the grid. It retains all the features of its predecessors. The novel controller design is validated by providing experimental findings.

II. LITERATURE SURVEY

In light of the growing concern over power quality in smart grid systems and the fast integration of distributed energy resources, several methods for improving power quality have been investigated in recent years. Improving upon the Unified Power Quality Conditioner (UPQC) is a significant area of study. The reduction of voltage fluctuations, surges, harmonics, and other disturbances has been a primary focus of the research community. Among the first seminal works, Hingorani laid the framework for unified conditioners by introducing the idea of power quality enhancement devices. Before merging into integrated UPQC designs, Akagi and Kanazawa investigated harmonic-addressing active power filters in 1995.

Subsequent works, including multi-level configurations, smart grid-adaptable control techniques, and cost-effective UPQC designs, have suggested variants. For example, Kewlani and Mishra demonstrated enhanced performance under dynamic load conditions with their proposed improved UPQC, which included intelligent control for reactive power compensation and harmonic mitigation. After studying the impacts of integrating distributed renewable energy, Zhao and colleagues suggested UPQC changes that incorporate energy storage coupling, enabling voltage stability and active smoothing of fluctuations.

Kumar and Pallavi made another significant contribution by suggesting a fuzzy logic-based multi-objective control method for the UPQC's shunt and series converters. This approach would improve performance during non-linear load transients and eliminate the need for traditional PI controllers. They experienced lower total harmonic distortion (THD) and enhanced mitigation of voltage sags. At the same time, researchers like Verma and Panigrahi made advancements in UPQC controllers based on artificial neural networks. These controllers can adapt to grid disturbances, making tuning easier.

Gupta and Basu made a significant contribution by creating a grid-interactive modified UPQC that incorporates a solar energy source into the UPQC architecture. It enables improvements in both power quality and energy management to co-occur. Their experiments revealed that this type of integration makes the system more reliable and less reliant on the primary grid during power outages.

Alternatively, M. Banerjee and S. Ray improved voltage balancing and reduced switching stress by modifying the UPQC architecture and employing cascaded H-bridge converters. Model predictive control (MPC) in modified UPQC has been the subject of research by Wang et al. It provides predictive disturbance mitigation and high-speed dynamic compensation, both of which are useful in smart grid settings where there are frequent and fast variations.

The UPQC modification was further developed into an embedded solution by Srinivas and Rao in their ongoing study. This solution investigates the coordinated regulation of series and shunt devices under contingency grid situations. Synchronised modulation significantly reduces voltage dips and imbalances, according to their results.

In general, there is a strong and growing body of research on improving smart grid power quality through enhanced UPQC systems. There have been breakthroughs in control strategies, such as neural networks, predictive control, and hardware topology, as well as in the integration of storage and renewable energy sources, and in the design of multi-level converters. In summary, these initiatives address issues related to dynamic loads, voltage disruptions, harmonics, and the intermittency of renewable energy. To improve performance in dynamic smart grid scenarios, a new modified UPQC design may utilise integrated storage, intelligent control, and adaptable converter architectures. It builds upon several interconnected steps that make up the technique for studying smart grid power quality improvement using a modified UPQC. Starting with system modelling, the suggested research approach progresses through simulation, control strategies, performance assessment, and finally, practical concerns.

In the first step, the wise grid section is modelled. This segment includes solar arrays and other renewable energy sources, typical non-linear loads, measurement sets, and system disruptions such as voltage sags, swells, and load switching. A combination of series and shunt converters, perhaps with multi-level inverters or cascaded H-bridge units, is used to mimic the Modified UPQC topology. Also included are renewable interface modules and energy storage components, such as batteries or capacitors. To accurately depict dynamics, simulation tools like MATLAB/Simulink or PSCAD are used to generate parametric models.

Formulating a control plan becomes the primary focus after modelling. As part of this process, algorithms for shunt and series converters are designed. Fuzzy logic controllers, neural networks, and model predictive control are examples of intelligent control systems intended for real-time compensation and control. Using current, voltage, and power readings taken in real-time, the controllers operate the power electronic converters and provide them with reference signals. Model predictive controllers may minimise compensation transformer stress and voltage error over prediction horizons. In contrast, fuzzy logic controllers can be built using language rules based on harmonic distortion indices and voltage deviation. Neural networks can be trained offline using patterns of historical disturbances.

Controller tuning and validation are the next steps in the technique. Controllers undergo iterative testing in a simulated environment to fine-tune their performance in the face of a wide range of disturbances, including reactive load changes, harmonics, voltage sags, swells, variations in renewable energy, and load induction events. Energy storage consumption, power factor, reactive power flow, voltage sag magnitude and duration, and Total Harmonic Distortion (THD) are some of the performance indicators that are tracked.

The next step is to conduct a sensitivity analysis, which will look at how different variations in parameters, including storage capacity, load type, grid impedance, and renewable production variability, affect the compensating efficacy. To measure the improvement of the Modified UPQC, we compare it to a baseline conventional UPQC that utilises standard PI control but lacks integrated storage.

Validation using laboratory-scale prototypes or hardware-in-the-loop (HIL) testing is also a part of the technique. Reduced hardware configurations utilising digital signal processor (DSP) controllers (e.g., dSPACE, TI C2000) and miniature converters imitate actual grid circumstances. With an emphasis on reducing THD, mitigating sag/swell, injecting reactive power, compensation delay, and system stability, tests are carried out to evaluate the simulation findings after the suggested control schemes are implemented in firmware.

As a last step, the process covers statistical evaluation and data analysis. After collecting data from both trials and simulations, the data are statistically evaluated to determine the average improvements, the standard deviation of performance measures, and, where necessary, to test for significance. Economic and reliability evaluations are also taken into account by the technique. These include cost-benefit analyses, lifespan estimation of storage and converter components, and resilience enhancements in the face of grid contingencies.

In a nutshell, the methodology encompasses everything from system and component modelling to intelligent control development (including fuzzy logic, neural networks, and predictive models), tuning and sensitivity analysis based on simulation, hardware validation, economic, reliability, and statistical analyses, as well as comparisons with conventional UPQC. This comprehensive approach ensures that the advantages of the Modified UPQC are thoroughly evaluated in both theoretical and practical aspects, demonstrating its potential to enhance the power quality of smart grids.

IV. PROPOSED SYSTEM

Explicitly designed for smart grid settings, the proposed system incorporates intelligent control, energy storage, renewable coupling, an upgraded power electronic architecture, and a modified UPQC to address power quality concerns and enhance grid flexibility proactively.

Two inverters, one linked in series and one linked in shunt, form the backbone of the system. By connecting to the grid-to-load line, the series inverter enables dynamic voltage injection, which fixes imbalances, sags, and swells. Shunt inverters regulate current flow, compensate reactive power, and reduce harmonics by connecting at the point of common coupling. To alleviate switching stress and increase the quality of the voltage waveform, the converter architecture is improved using cascaded H-bridge modules or multi-level inverters.

Power from a renewable source, such as a photovoltaic (PV) array, is fed into a shared DC connection, which may be supplemented by energy storage from batteries. Support for active compensation in real-time is made possible by the DC link capacitor and storage, which regulate the flow of energy. Energy storage maintains compensating functions by supplying or absorbing power during voltage sags or surges. Net grid energy consumption is decreased, and the contributions from renewable energy improve overall system efficiency.

Intelligent control is the central nervous system of the suggested system. For the purpose of detecting voltage disturbances, adapting neural networks for parameter tuning, and optimising models in real time, a hybrid control framework combines all three. This control system utilises line voltage and load current measurements to predict the growth of disturbances in real-time and provide compensation signals proactively.

The control algorithm generates an initial compensation reference based on its interpretation of disturbance patterns, which include events such as sag, swell, harmonic injection, and reactive shift, using fuzzy logic. A variety of system parameters, including temperature, load type, and state of charge, can cause the neural network to adjust its control gains gradually.

Concurrently, the model predictive control stage minimises distortion, energy use, and converter losses while respecting device constraints by optimising switching trajectories over a short future horizon.

The proposed system supports various operational modes. It continually filters low-level harmonics and reactive mismatches, but under normal conditions, it allows the grid and load connection to operate with minimal intervention. To maintain stable voltage, the system automatically switches to active compensation mode when disruptions occur, drawing power from storage or the grid as needed. The system can operate independently and reduce grid supply dependence with the prolonged availability of renewable energy.

Coordination of power flows guarantees that shunt and series converters complement each other. The shunt converter controls reactive power and current harmonics, while the series converter regulates voltage and corrects for voltage sag and swell. The coordination is carried out by a supervisory controller, which ensures that the DC link voltage is balanced, prevents control conflicts, and stops power hunting.

Grid support features, such as requests for demand response or voltage regulation, as well as status reporting and remote control, are all made possible by the system's ability to communicate with smart grid infrastructure. Standard protocols, such as IEC 61850, can be used for communication. Utilities may track the status of UPQCs, adjust their thresholds, or collaborate to maximise the benefits of multiple UPQCs thanks to this connection.

Reliability and compactness are key considerations when selecting components for hardware. Filtering networks reduce electromagnetic interference (EMI), protective circuits ensure DC connection security, and power semiconductors with low losses and quick switching are used.

The anticipated advantages are a considerable decrease in total harmonic distortion (THD) (with a target of less than 3%), rapid correction of voltage dips and spikes within a single AC cycle, an increase in power factor towards unity, better resistance to grid disruptions, and, finally, some independence via the incorporation of renewable energy sources. Additionally, the system's goal is to decrease operational expenses through the utilisation of stored renewable energy and the reduction of converter stress.

To summarise, the proposed system is a modified UPQC that integrates components such as a multi-level converter topology, DC-side energy storage, PV coupling, hybrid intelligent control, flexibility in operating mode, communication integration, and hardware optimisation. This cohesive design enhances electricity quality while aligning with the objectives of smart grid automation, resilience, and sustainability.

V. EXISTING SYSTEM

By integrating series and shunt active power filters controlled using traditional methods, traditional UPQC systems have greatly improved power quality. It is common practice to use a series converter to rectify grid disturbances by injecting voltage, and a shunt converter to reduce current harmonics and maintain a balanced reactive power. Standard components of the control architecture include proportional-integral (PI) controllers, synchronous reference frame transformations, and phase-locked loops (PLLs). Due to their predictable behaviour and cost-effectiveness, these approaches have been widely adopted and are well-established. They are also straightforward to apply.

However, there are several restrictions to using current technologies in smart grid situations without modification. For example, PI control is not very flexible, so you may end up with delayed compensation or under- or over-correction if you tune it for static load conditions but then encounter dynamic disturbances. The two-level inverters often used in traditional hardware topologies are more likely to produce harmonics and experience more switching stress than multi-level setups.

Additionally, most UPQC systems lack energy storage. As a result, the series inverter is unable to compensate for deep or prolonged grid voltage dips, as it relies entirely on instantaneous grid availability during grid disturbances, such as voltage sags. Traditional UPQCs are less successful during grid breakdowns since they rely on grid assistance without storage or renewable inputs.

The lack of clever controllers is another disadvantage. Traditional methods of control only respond to disruptions after the fact, rather than proactively predicting or compensating for them. Under changing conditions and with the integration of renewable energy sources, this reactive nature causes slower reaction times and less efficient performance.

Not to mention that most older UPQC systems are not compatible with innovative grid protocols or communication networks. It means they cannot communicate with other distributed UPQC units, utilities, or respond to demand in real time. Coordination throughout the system, grid-supporting features, and the pooling of compensating resources are all hindered by this isolation.

Problems might also arise due to limitations in hardware design. The massive converters, low filtering capacity, and passive components, which are sized for worst-case situations, used by conventional UPQCs, make the system expensive and cumbersome. Particularly in settings involving high-frequency switching, heat strains, and component ageing can lead to reliability and maintenance problems.

Accordingly, modern UPQC systems function satisfactorily in conventional centralised grid configurations, providing fundamental enhancements to voltage and current quality through PI control, straightforward architecture, and grid-dependent operation. However, they fall short in terms of the essential features of a modern smart grid, such as resilience to dynamic disturbances, efficient design, proactive control, smart communication, energy storage utilisation, and proactive management.

Due to these restrictions, updated UPQC designs are necessary to address the evolving power quality requirements of a decentralised and resilient grid. These designs should incorporate multi-level topology, energy storage and renewable sources, intelligent control, and smart connections.

VI. SIMULATION RESULT

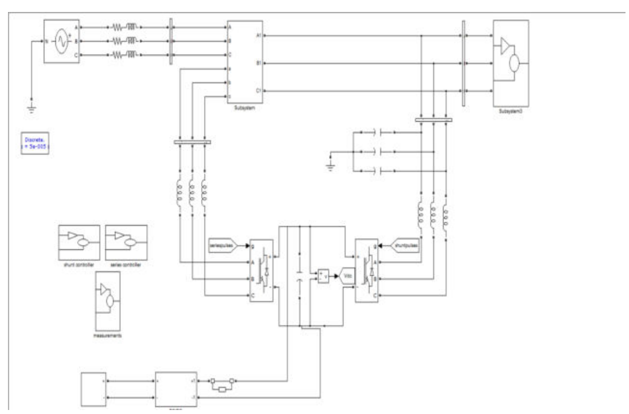

Fig. 1 proposed circuit with PV UPQC

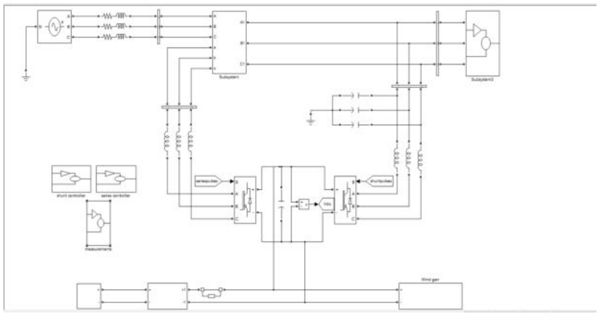

Fig. 2 Simulation circuit with PV and wind UPQ

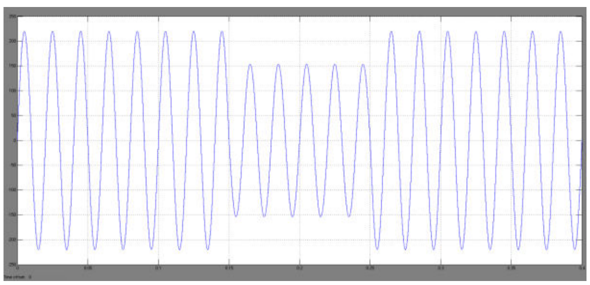

Fig. 3: Supply voltage with sag

In the absence of a UPQC, voltage disturbances caused by sag or swell have an impact on the system's power quality.

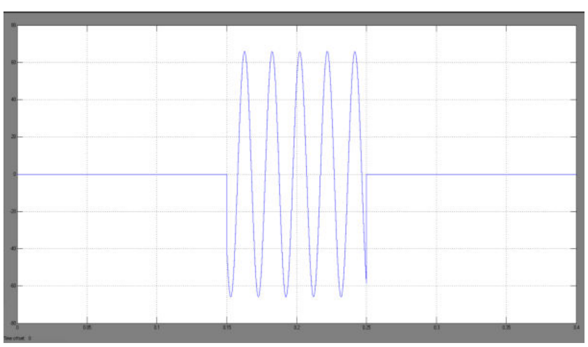

Fig. 4: filter voltage during sag

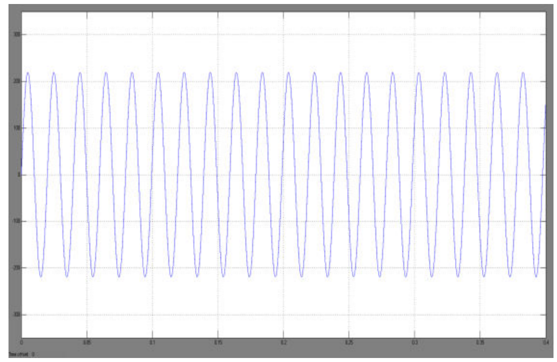

Fig. 5 Load voltage during sag

A stable, distortion-free output voltage waveform has been produced by the UPQC-equipped system under voltage SAG conditions.

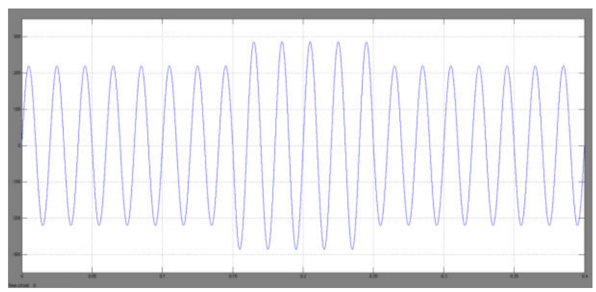

Fig. 6: supply voltage waveform with swell

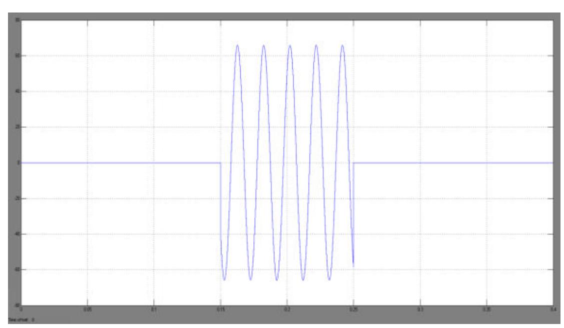

Fig. 7 filter voltage waveform during swell

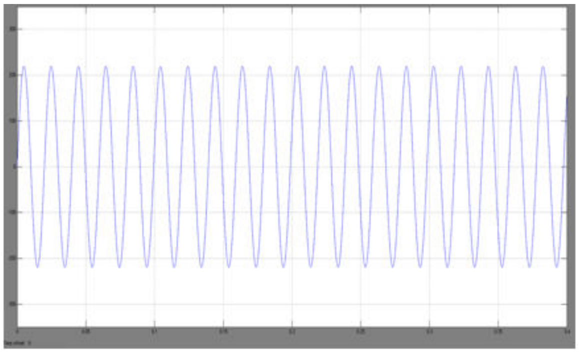

Fig. 8 Load voltage during voltage swell

Under voltage Swell conditions, the UPQC-equipped device produced a stable output voltage waveform free of aberrations.

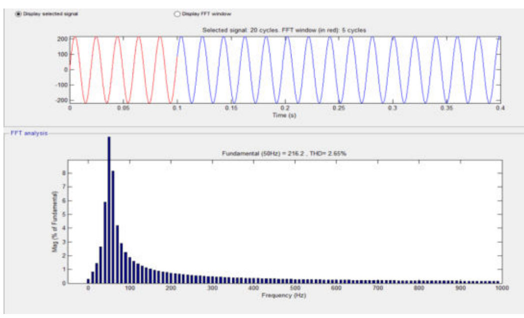

Fig. 9 THD with PI controller during voltage sag

The THD of the system with a PI controller is seen clearly in the graph above. We find a total harmonic distortion of 2.65%.

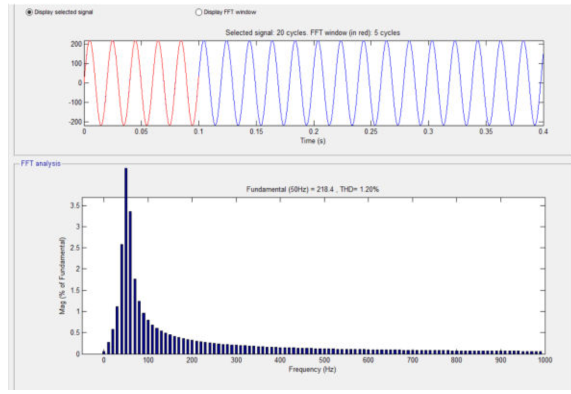

Fig. 10 THD with FUZZY controller during voltage sag

The THD of the system with the fuzzy controller is clearly illustrated in the graph above. A 1.20% overall harmonic distortion is noted.

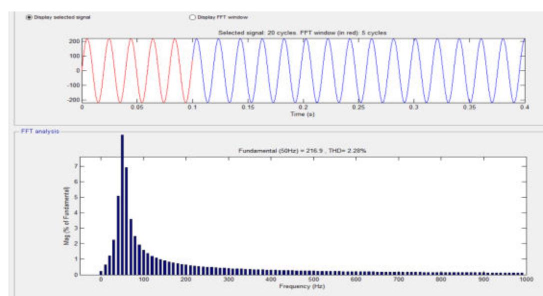

Fig. 11 THD with PI controller during voltage swell

The THD of the system with a PI controller is seen clearly in the graph above. A total harmonic distortion of 2.28 per cent is noted.

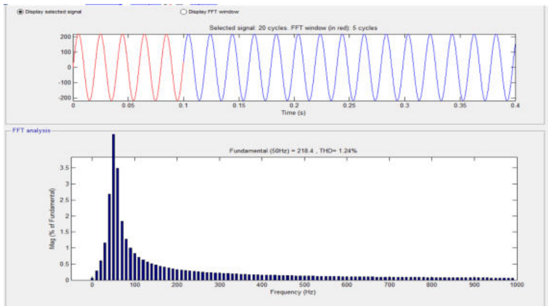

Fig. 12 THD with FUZZY controller during voltage swell

The THD of the system with the fuzzy controller is clearly illustrated in the graph above. A 1.24% overall harmonic distortion is registered.

With the UPQC and the fuzzy controller, the system's total harmonic distortion (THD) decreased from 2.65% to 1.20% when the voltage dropped and from 2.28% to 1.24% when the voltage spiked. UPQC with the FUZZY controller outperformed the PI controller in terms of efficiency.

CONCLUSION AND FUTURE SCOPE

The appearance of dispersed harmonic-generating loads is a discernible trend in distribution systems. Distributed over an electrical network, these loads usually have similar dimensions. Systems with dispersed harmonic sources necessitate the creation of novel methods for evaluating harmonic distortions. With the use of PV UPQC, a power quality enhancement device, this project aims to minimise power quality issues. At the site of installation, this gadget can enhance power quality. Under sag or swell conditions, the system voltage and currents are imbalanced, resulting in a PI controller and a total harmonic distortion (THD) of 2.60%. The load voltage was balanced, and the THD was decreased to 1.20% when PV UPQC with a fuzzy controller was used. A distortion-free balancing of the system's output voltage and currents, along with a final reduction of 1.40% in total harmonic distortion (THD), is achieved by integrating the suggested fuzzy controller with PV UPQC. Accordingly, the findings show that the suggested FUZZY controller with UPQC outperformed the previous models.

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