Review: Active Power Filters for Power Quality Improvement

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Abstrac : The purpose of this study is to examine the evolution of active power filter (APF) technologies, which are frequently employed to reduce harmonics in utility power lines. This review may also be classified as a "tutorial-type study," since it gives a comprehensive overview of APF technologies while avoiding the boring minutiae without losing sight of the primary point. It is anticipated that by taking this approach, more power engineering readers would become interested in this vital and rapidly developing area. The talk begins with a quick introduction of harmonic distortion issues and their effects on the quality of electric power. The functioning of typical APF topologies, such as shunt, series, and hybrid APFs, is well explained. A discussion of several sorts of reference signal estimate extraction methodologies follows. The use of the p-q and extension p-q theorems to extract the reference signals is discussed in depth, as they are the most often used in real APF systems. Finally, a summary of APF control techniques is given. There is also a brief description of the APF-solar photovoltaic system. Important references are provided at the conclusion of the text to aid readers who want to learn more about the subject.

The application of new technical solutions such as Custom Power (CP) and Flexible AC Transmission Systems (FACTS) Devices has risen as the cost of power electronic devices has decreased and the efficiency of both power converters and energy storage components has improved. One of the CP devices is the Active Power Filter (APF), which may reduce harmonics, reactive power, and unbalanced load currents on the load side. The pros and cons of each offered approach are described in this research, which is a complete overview of APF investigations. The research also aids researchers in determining the best control techniques and power circuit layout for APF applications.

***Index Terms* – Active Power Filter, Power flow control**

I. Introduction

Although power quality (PQ) issues in power utility distribution systems are not new, their consequences have only lately become widely recognized. Over the last decade, advances in semiconductor device technology have fueled a revolution in power electronics, and there are signs that this trend will continue [1]. The growth in PQ-related difficulties is attributed to power electronics-based equipment such as adjustable-speed motor drives, electronic power supplies, DC motor drives, battery chargers, and electronic ballasts [2],[3]. In a power distribution system, these nonlinear loads appear to be major causes of harmonic distortion. Nonlinear loads create harmonic currents, which are fed back into power distribution networks via the point of common coupling (PCC). Harmonic voltages arise as harmonic currents flow through the system's line impedance, creating distortion at the PCC.

Harmonics have a variety of negative consequences for the distribution system. They are divided into two types: short-term and long-term. Excessive voltage distortion causes short-term consequences, which are generally the most visible. Long-term impacts, on the other hand, are frequently undiscovered and are generally linked to increasing resistive losses or voltage stresses [4]. Furthermore, nonlinear loads' harmonic currents can interact negatively with a broad range of power system equipment, most notably capacitors, transformers, and motors, resulting in extra losses, overheating, and overloading. Harmonics have a variety of negative consequences for the distribution system. They are divided into two types: short-term and long-term. Excessive voltage distortion causes short-term consequences, which are generally the most visible. Long-term impacts, on the other hand, are frequently undiscovered and are generally linked to increasing resistive losses or voltage stresses [4]. Furthermore, nonlinear loads' harmonic currents can interact negatively with a broad range of power system equipment, most notably capacitors, transformers, and motors, resulting in extra losses, overheating, and overloading. The usage of passive components, while simple, does not always respond appropriately to the dynamics of power distribution networks [9]. These passive filters have advanced to a high level of complexity throughout time. Some have even been adjusted to avoid certain harmonic frequencies. Inductance, capacitance, and resistance components are designed and adjusted to control harmonics in traditional passive filters. Figure 2.3 depicts common passive filter types and combinations. The most popular and cost-effective passive filter is the single-tuned "notch" filter [8]. The notch filter is series-tuned to provide low impedance to a certain harmonic current and is linked in shunt with the power distribution system. As a result of the filter, harmonic currents are deflected from their regular flow route. The high-pass filter (HPF) is another common form of passive filter [7]. A HPF will pass through a significant percentage of all harmonics above its corner frequency. As illustrated in Figure 1, HPF usually takes one of three forms. The first-order is rarely utilised since it is characterised by high power losses at fundamental frequency.

The second-order HPF is the easiest to use while yet offering effective filtering and low fundamental frequency losses [9]. The third-order HPF outperforms the second-order HPF in terms of filtering performance. The third-order HPF, on the other hand, is not widely utilised for low-voltage or medium-voltage applications since the cost, complexity, and reliability aspects do not support it [8].

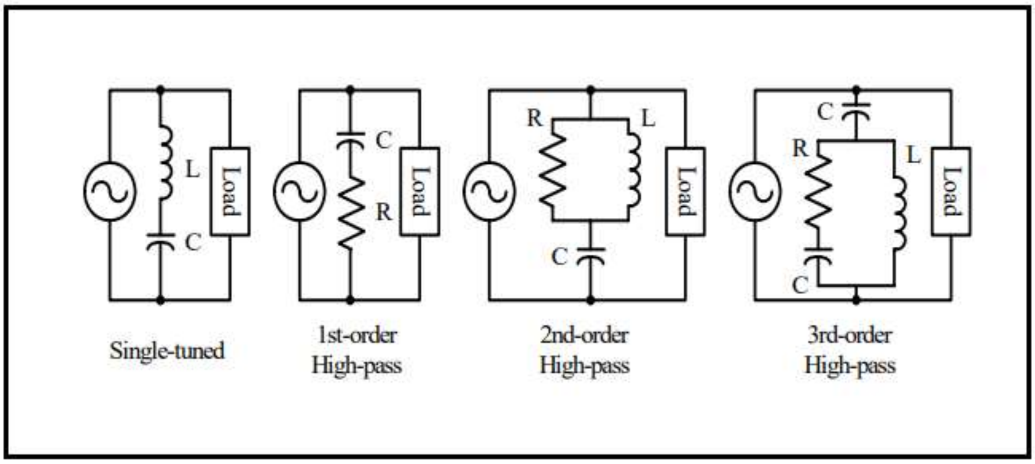

Fig.1. Common types of passive filters and their configurations

The passive filter, although being simple and inexpensive, has numerous flaws. Because the harmonics that need to be suppressed are generally of low order [4], [9], the filter components are rather large. Furthermore, the source impedance affects the compensating properties of these filters. As a result, the filter's design is strongly influenced by the power supply to which it is linked [8]. Passive filters are known to generate resonance, which affects the power distribution system's stability [9]. The filtering characteristics are influenced by the frequency fluctuation of the power distribution system and component tolerances. When the frequency fluctuation is significant, the size of the components becomes problematic [8], [9]. Passive filters may not be able to fulfill future versions of a specific Standard as regulatory requirements become more rigorous. This may necessitate the installation of new filters.

II. DIFFERENT TECHNIQUES FOR ACTIVE POWER FILTER CONTROL

The three-level inverter is used as a series active power filter to reduce harmonic voltage taken from a nonlinear load, as proposed by the author [1]. For the fundamental frequency, this filter functions as a zero impedance, but for harmonic frequencies, it acts as a high resistor. The majority of previously reported three-phase series active power filters are based on two-level inverters with traditional controllers, which need a complex and difficult mathematical model. A fuzzy logic controller is utilised to solve this problem, and it is expanded to a three-level SAPF.

The concepts of operation and design of a fuzzy logic controller algorithm to regulate harmonic voltages are presented in this paper. The suggested algorithm's feasibility is tested via computer simulation. Source voltage is sinusoidal and in phase with source current, according to the data. The proposed solution has a low total harmonic distortion, indicating the efficacy of the fuzzy logic control method given.

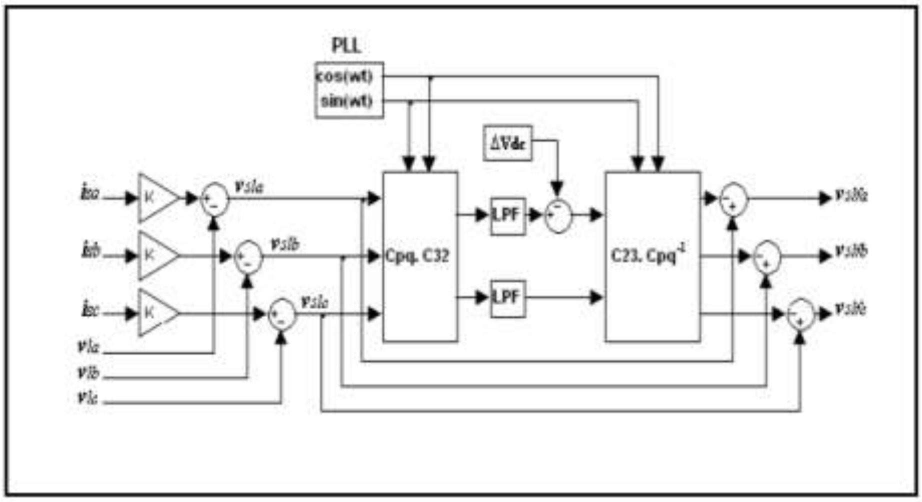

Fig.2. Block diagram of voltages references determination

The purpose of this paper is to demonstrate the benefits of utilising a multilayer series active filter instead of traditional controllers while using fuzzy logic controllers. Not only were the harmonics decreased to an acceptable level, but the transient reaction time was also lowered. In addition, the utility power factor was adjusted. The series active power filter's steady state performance has been enhanced thanks to the fuzzy logic controller. Simulation is used to demonstrate the efficacy of the suggested strategy.

Deep integration of renewable energy resources, such as solar photovoltaic (PV) and wind turbine (WT) energy, is largely dependent on low-cost technical improvements in worldwide emissions and accurate power quality procedures. Grid-connected inverters are essential components in cutting-edge distributed generating systems. For power conversion, the inverter connects renewable energy sources and power distribution network systems. Several current and voltage harmonics impact the system performance in grid-connected systems. Similarly, the performance of power networks and systems in terms of power quality is influenced by extremely unstable devices, as well as the rising need for nonlinear loads and renewable energy supplies. Passive filters (PFs), static var generators, and active power filters are all viable solutions to these issues (APFs). The employment of PFs in a high-power system, on the other hand, increases the system's cost, size, and weight. This research seeks to evaluate the most modern APFs by lowering the number of power switches and focusing on grid-connected inverter cost, size, and weight. Several research examined and assessed reduced-switch-count APF inverter topologies under single-phase and three-phase systems, such as AC–AC, back-to-back, and common leg. Recent research has focused on cost-effective methods for reducing the number of components, transformer-less inverters, multilayer and multifunctional inverters based on the APF in PV, and wind energy conversion systems. The existing approaches for building improved inverter-based devices for renewable energy systems, as well as their limits, are reviewed with reasons. As a result, this evaluation may be able to assist industry researchers in improving power quality in PV and WT energy systems, as well as power distribution network systems.

This technique [2] gives state-of-the-art and powerful viewpoints on APF and grid-connected renewable energy systems' transformer-less, passive components. Researchers, manufacturers, and engineers dealing with harmonics and power quality concerns can benefit from this review's wide viewpoint. Innovative and unique improvements in the field of grid-connected inverters have been reported to improve the power quality of the DER and DPGS. Back-to-back inverters, AC-to-AC inverters, and common-leg inverter configurations are the primary research directions in decreased switch count inverters with APF topologies. As a result, power quality enhancement techniques such as PFs, APF, HAPF, hybrid filters, UPQC, and STATCOM are used.

APFs are well-established technology that serve as a vital link between distributed grid systems and harmonic pollution. Consumers may choose from a variety of well-developed and large-capacity modern APF technologies on the market today. The need for APFs has been evaluated in order to minimise the cost, volumetric size, weight, THD, power loss, and efficiency of power semiconductor components, auxiliary circuits, and coupling transformers. The current grid-connected APF PV inverters and wind energy conversion inverters are also studied, evaluated, compared, and commented. The utilities will support the installation of APF technology alongside nonlinear loads in order to maintain power quality at an acceptable level in the long run. SVG and STATCOM are the two new APF concepts presented in this article. In grid-integrated distribution systems, the APF is an effective solution for power quality issues such as harmonic reduction, voltage control, load balance, power factor correction, and neutral current compensation. As a result, sophisticated SAPF systems might include dual-terminal inverters, shared legs between inverters and rectifiers, and the replacement of split capacitor designs.

The author provided [3] a research of the proposed technique, which is based on a series active power filter based on a photovoltaic array (PV-SAPF) that is controlled by a conventional PI utilising a pulse width modulation inverter (PWM). The suggested system is linked to the grid to feed linear and nonlinear loads in order to handle deep sags, swells voltage, voltage distortion, and power factor crushing induced by electrical disturbances. On the other hand, when the network is not impacted and after adjustment, the extra energy is pumped into the mains. The PV-SAPF is carried out in the MATLAB / Simulink environment to demonstrate the efficacy of the intended system. The suggested system's capabilities and efficiency in mitigating harmonic voltage distortion, correcting voltage sag and swell, improving power factor, and improving power quality were demonstrated by simulation results.

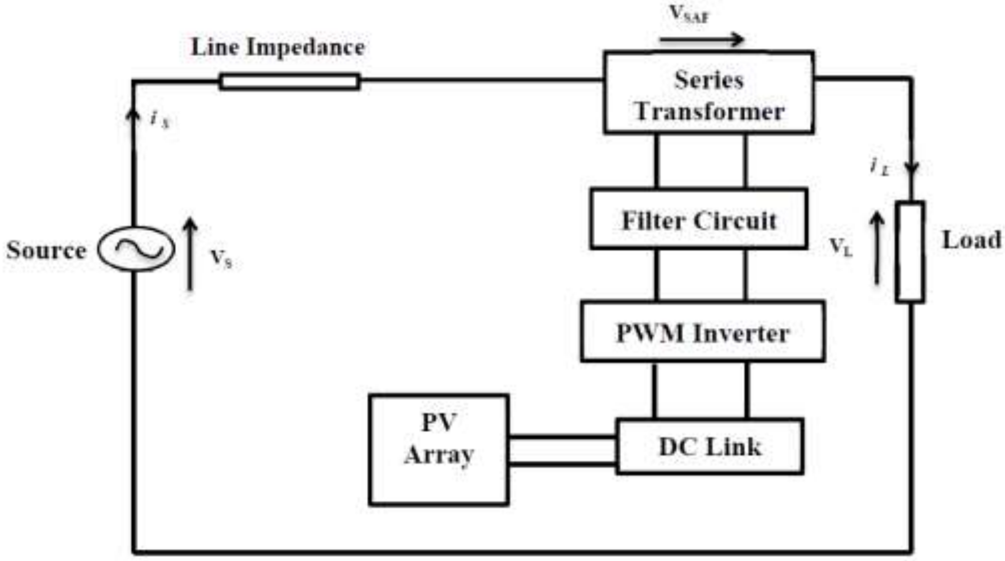

Fig.2. General structure of power system compensated by SAPF and PV

A photovoltaic series active power filter has been designed and tested as a sinusoidal current source in phase with the mains voltage. The error signal created between the load voltage and a pre-established reference controls the amplitude of the fundamental current in the series filter. The control provides for excellent harmonic distortion reduction as well as load voltage management.

Photovoltaic looks to be one of the most promising renewable energy sources for the future, with applications in a variety of fields. The SAPF-PV system is suggested in this study to evaluate its usage in this regard. It is evident from the results that by employing this strategy based on the PLL method, PV power may be efficiently collected by PV systems and injected to feed loads and supply electricity to the mains. The PV-SAPF easily handles both balanced and unbalanced circumstances, injecting the necessary voltage component to quickly rectify any abnormality in the supply voltage, ensuring that the load voltage remains balanced and steady at the nominal value.

The use of a modified symmetrical sinusoidal integrator (MSSI) to manage a unified active power filter integrated with a solar photovoltaic array (UAPF-PV) is presented in this paper.

The solar photovoltaic (PV) array is directly connected with the UAPF-PV system's DC-bus in this three-phase four-wire single stage UAPF-PV system. The fundamental positive sequence signals of distorted load currents and point of common coupling (PCC) voltages are extracted using two positive sequence extractors based on MSSI, which are then used to generate the reference signals for the shunt active filter and series active filter, respectively. While collecting maximum power from the PV array, the shunt active filter keeps the grid currents balanced and sinusoidal. Regardless of harmonic distortions and sag in PCC voltages, the series compensator keeps the load voltage sinusoidal and in phase with the PCC voltage. Under unsymmetrical loading, harmonic distortion, sag in PCC voltage, and change in irradiation of solar PV array, the system performance is thoroughly investigated using Matlab Simulation.

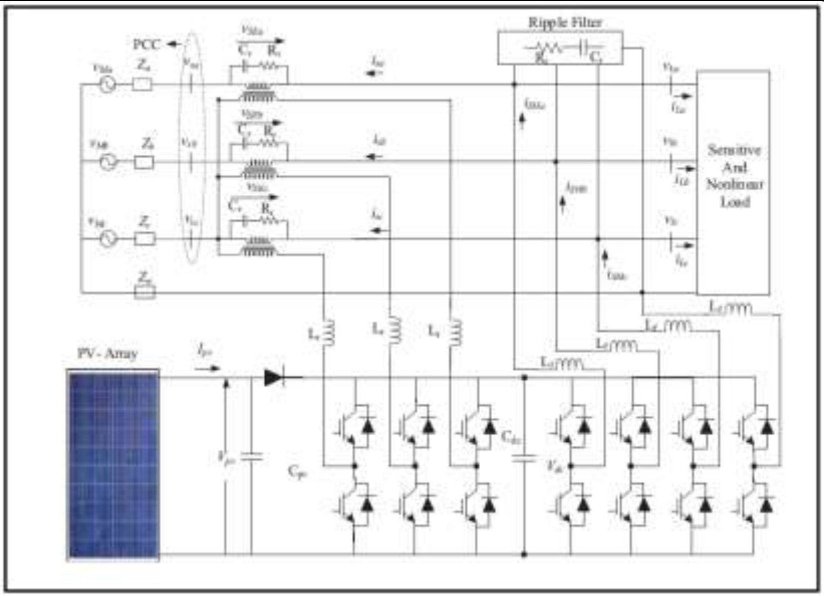

Fig.3. Configuration UAPF-PV System [4]

Simulation has been used to examine the steady state and dynamic behaviour of a three phase four wire single stage UAPF-PV system operating in a weak grid environment. The balanced positive sequence load currents are estimated using a modified symmetrical sinusoidal integrator (MSSI), which is then utilised to produce references for the shunt active filter.
During sag conditions, the series active filter injects voltages in phase with the fundamental component of PCC voltages, compensating for PCC voltage distortion. The UAPV-PV system not only improves power quality, but it also creates clean energy through a PV array incorporated into its DC bus. The system's performance has been confirmed well under a variety of test situations, including irradiation modification, unsymmetrical distribution system loads, and fluctuations and distortions in PCC voltage.

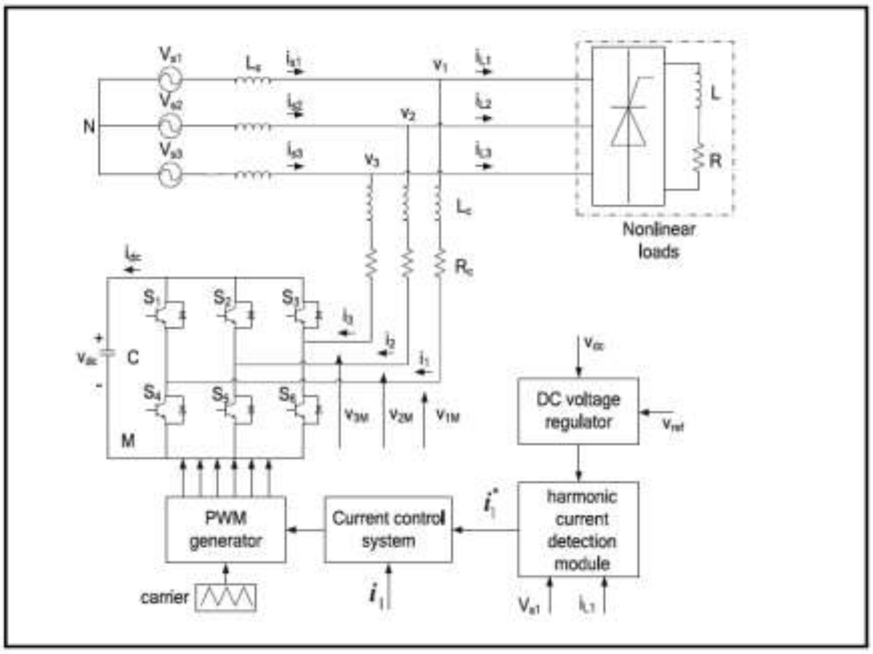

Fig.5. Schematic of active power filter [5]

In this study, a terminal sliding controller is used to build an adaptive fuzzy-neural fractional-order current controller to track the ideal current of an active power filter (APF) with limited time control capability. To achieve high precision and finite-time control characteristics with assured stable sliding surface, an adaptive fractional-order finite-time controller utilising terminal sliding method is proposed first. Then, to estimate the unknown APF system nonlinearities, a fuzzy-neural estimator is presented. The proposed adaptive fuzzy-neural fractional order terminal sliding controller is validated using numerical analysis to track the ideal current and minimize harmonic distortion.
For harmonic suppression and current tracking in the APF, this technique [5] uses a fractional-order adaptive fuzzy-neural terminal finite-time sliding controller. To begin, a fractional terminal sliding surface is developed to ensure the converging characteristics are restricted in time. To estimate unknown system nonlinearities, the fuzzy-neural estimator was created. The tracking effect and durability of the developed adaptive fractional-order fuzzy-neural terminal finite-time sliding control method are demonstrated through simulation. The following study phase will look at the constraint problem that might cause the system to decline.
The utilisation of loads has increased dramatically in recent days, raising concerns about power quality among power system and electronics professionals. Voltage and harmonic distortions are common in utilities due to the vast number of non-linear power equipment. The coupling of the Series active power filter SAPF with a PV source is considered by the author [6]. The PV based on the SAPF is designed to correct for voltage variations or disruptions induced by power quality concerns in the system. The suggested system comprises of a PV source linked to the DC link through two dc-dc converters, the first of which extracts the PV source's maximum power using pulse with modulation PWM signals provided by the maximum power point tracker MPPT controller. In

addition to a voltage source inverter VSI and a series injection transformer, the second converter is utilised to regulate the high voltage side of the converter through closed control loops utilising a Fuzzy Logic Controller FLC. MPPT and closed control loops produce PWM signals to the switching devices of dc-dc boost converters in order to extract maximum PV power and keep the bus voltage within its limits and around its reference values, despite variations in the DC link during the compensation of the required energy. The suggested topology is modelled using Matlab Simulink software, with simulation results demonstrating that the proposed PV-based SAPF may effectively decrease voltage sag and harmonic issues.

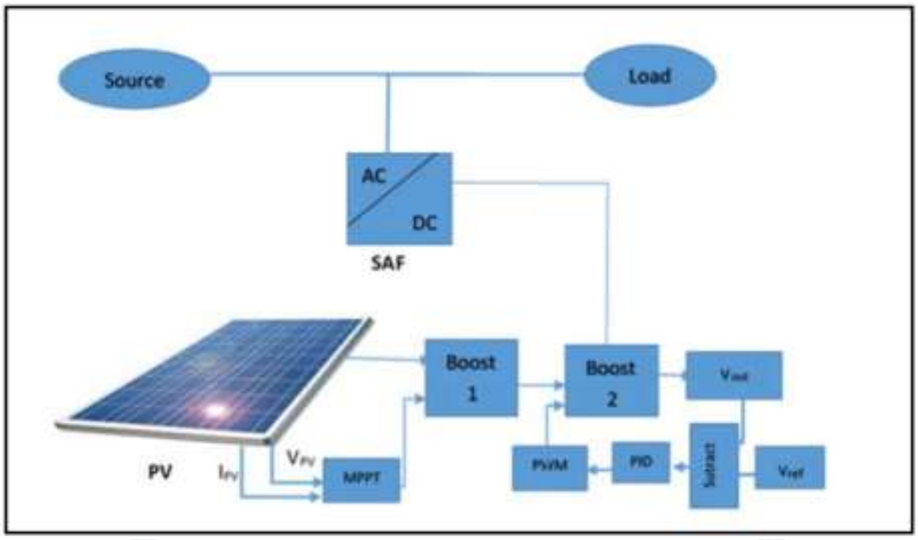

Fig.6. Overall block diagram of PV-SAPF [6]

The design and modelling of a new SAPF system supplied by a renewable energy source is presented in this technique [6]. Two traditional boost converters are also included in the proposed system to compensate for reactive power, harmonic, and voltage sags at load. An MPPT algorithm is used in the PV system to harvest the most power from the panels. The fuzzy logic controller was in charge of the second Boot. The simulation work was done in Matlab Simulink, and we can see that with the SAPF-PV, the THD of the source voltage is decreased from 33,33% to 2,94%. Future work will be an experimental result to computer with simulation works.

The dynamic voltage restorer (DVR) is a series active filter that protects sensitive loads from power quality concerns including voltage sag, swell, harmonics, and disturbances. This indicates that the DVR can handle power quality issues at the load terminal. Harmonic is a severe power quality issue that pollutes the distribution network, leading end-user equipment to fail to operate owing to voltage, current, or frequency disruptions. The DVR was utilised as a proposed approach to minimise voltage sag and swell in a distribution network coupled with an energy storage system and a mini-hydro turbine system, according to the author [7].

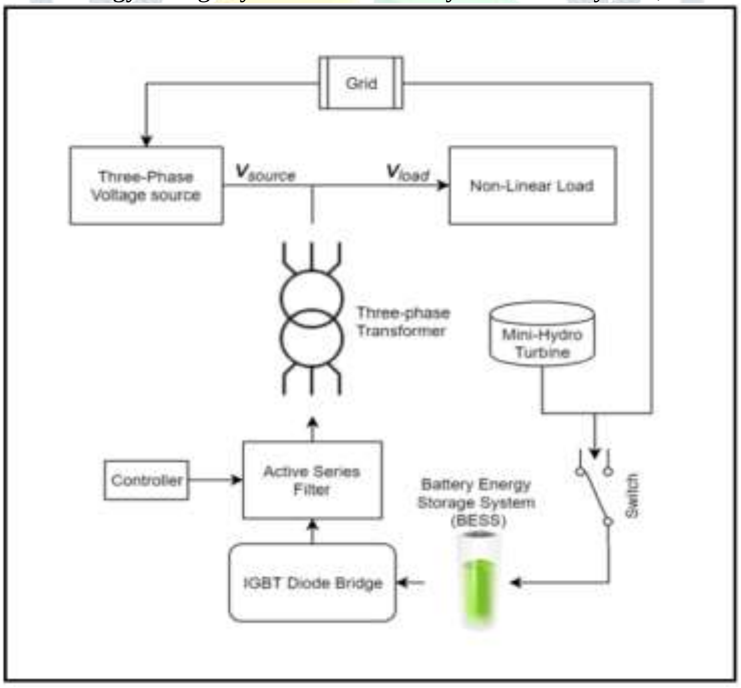

Fig.7. DVR utilized in a microgrid system installed with the mini-hydro turbine [7]

The relevance of DVR for reducing power quality concerns in microgrids coupled to battery storage and mini-hydro turbine systems was highlighted in this manner [7]. The results demonstrate that the larger the proportion of voltage sag, the more a big DC voltage must be injected to mitigate it. The energy storage system must pump 224VDC into the microgrid system to compensate for 70% of voltage sag. This means that a battery management system is required to efficiently supply consistent voltage during battery draining and charging modes. The voltage injection mechanism is unable to produce and sustain the needed amount of voltage injection because the battery's initial state-of-charge is less than 100 percent. Furthermore, the suggested DVR approach may be regarded as a highly dependable, effective, and quick-response technology for improving power quality. It is also an excellent device for protecting sensitive loads from voltage sags and swells for a limited period of time. The case study of DVR with mini-hydro turbine system shows that it can work in a renewable energy generating scenario.

Author suggested [8], an adaptive fuzzy-neural-network (AFNN) control for active power filter (APF) as current controller utilising nonsingular terminal sliding mode control to mitigate the influence of unknown external disturbances and modelling uncertainties. To begin, a dynamic model for APF is created, which takes into account both system parameter changes and external disturbances. Then, for the existing control system, a nonsingular terminal sliding mode control based on back stepping (NTSMB) technique is proposed to overcome the singularity point problem and achieve rapid and finite time convergence. Furthermore, to increase the robustness of NTSMB, AFNN is intended to reduce the necessity of previous knowledge of system characteristics. The AFNN approach is based on the NTSMB, in which the parameters are updated online using an adaptive rule developed from the projection method and Lyapunov stability analysis to ensure tracking performance and stability of the closed-loop system. In comparison to traditional sliding mode control, simulation tests show that the suggested control techniques outperform traditional sliding mode control in both steady state and transient operation. In order to validate the performance of the proposed controller, experimental findings employing a completely digital control system are presented.

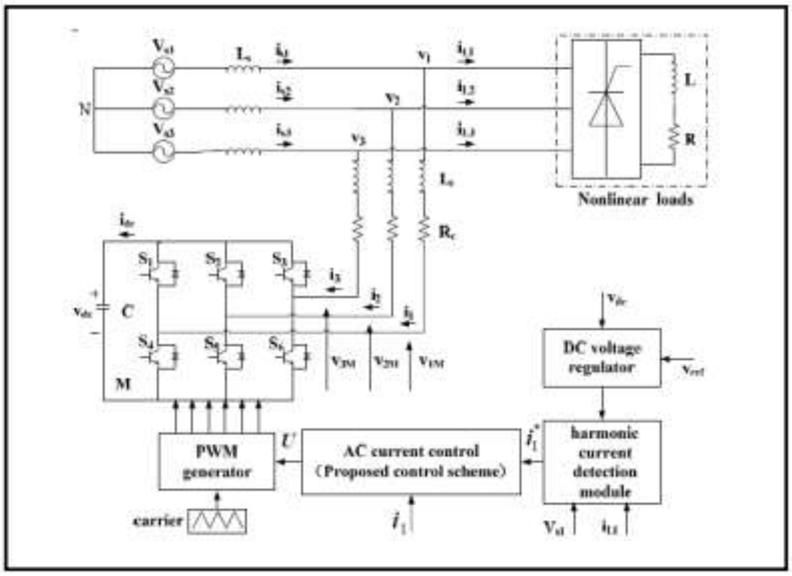

Fig.8. Block diagram for APF [8]

For active power filters with unknown disturbances and parameter perturbations, this approach [8] proposes an adaptive fuzzy-neural-network control utilising nonsingular terminal sliding mode control. The parameters of the AFNN may be adaptively updated using Lyapunov analysis, and the suggested control approach ensures the closed-loop system's stability. For various operating circumstances, the suggested controller's performance is examined and compared to that of a standard sliding mode controller. The modelling and experimental findings show that the suggested control schemes function well, exhibiting good dynamic performance, stability, and resilience in a variety of situations.

Because it is difficult to develop an appropriate mathematical model for APF due to its nonlinearity and coupling, the suggested control method, which has the distinct advantage of being model-free, has a lot of promise for usage in APF. AFNN can accomplish precision and finite-time control thanks to NTSMB, and the adaptive laws for system parameters are derived from the Lyapunov stability theorem to assure convergence and stable control performance. The suggested controller may also reach good performance, according on simulation and experimental findings.

To the best of the authors' knowledge, no AFNN-based major control design for APF with parametric uncertainties and external disturbances has been described that concurrently addresses the concerns of finite-time control and system stability guarantee. The suggested method is unique in that it uses a synthesis of AFNN and NTSMB for APF for the first time to obtain superior control performance.

In addition, the suggested controller has a broad application and may be utilised in a variety of settings, including grid-connected converters, programmable ac power supplies, and so on. It's worth noting that the suggested control approach has significant advantages for big multilevel converters like five- or seven-level converters, which need a more complicated mathematical model.

The combination of a series active power filter (SAPF) with a fuel cell (FC) source was proposed by the author [9]. The FC based on the SAPF is designed to adjust for voltage variations or system disruptions caused by power quality concerns. A fuel cell source is coupled to the DC connection through two DC-DC converters, the first of which harvests the maximum power from the FC source using pulse width modulation (PWM) signals provided by the maximum power point tracker (MPPT) controller. In addition to a voltage source inverter (VSI) and a series injection transformer, the second converter is utilised to regulate the high voltage side of the converter using closed control loops. MPPT and closed control loops generate PWM signals to the switching devices of DC-DC boost converters in order to extract maximum fuel cell power and maintain the bus voltage within its limits and around its reference values, despite fluctuations in the DC link during the compensation of the needed energy.

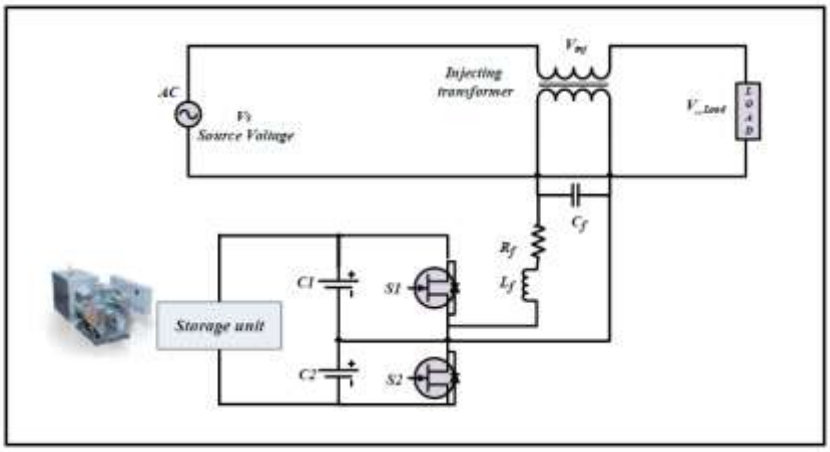

Fig.9. General configuration of the SAPF-FC system [9]

A SAPF that relies on an FC source was utilised in this brief research to minimise voltage disturbances such as sag-swell and harmonics. A conversion chain is connected to the renewable source FC in this approach [9], and the DC side's control strategy is based on two combined controllers. First, the MPPT controller is used in the first DC-DC boost converter to extract the most power from the FC, while closed control loops keep the high side voltage of the second DC-DC converter constant during the disturbances. The proportional integral PI compensator's duty cycles are precisely regulated in order to counteract DC bus fluctuations and extract the maximum by producing PWM signals to the DC-DC converters' switching components. Renewable energy, according to the findings, can be an effective solution to power quality concerns.

Because of the widespread usage of power electronics and voltage instability, improving power quality confronts a number of important challenges. An active power filter is used to solve these various power quality issues. Shunt, series, unified power quality conditioner, and hybrid active power filters are the four major types of active power filters. Shunt active power filters are commonly used to reduce source current harmonics and adjust reactive power for improved power factor. The series active power filter is commonly used to reduce voltage fluctuations (sags, swells, transients, dips, distortions). For all voltage and current issues, the unified power quality conditioner is employed. The three phase three-wire series active power filter, as proposed by the author [10], is used alone to mitigate all power system problems (voltages and currents) for this case study, such as voltage sag, voltage swell, voltage harmonics, and source current harmonics, in order to comply with the harmonics limits set forth in IEEE 519-1992 and IEC 61000-4-7 standards. The major causes of source current harmonics are 1) a distorted voltage source and 2) non-linear loads. In the event of a distorted voltage source, the series active power filter may efficiently remove source current harmonics. As a result, the series active power filter may be utilised alone to enhance power quality for all of the voltage and current issues discussed in this case study.

The Series Active Power Filter may be utilised on its own to minimise power system difficulties (voltage and current issues) and enhance overall power system quality in this case study. When the SEAPF is used for the system under investigation, it is discovered that: 1) the SEAPF has a good effect on source current harmonic elimination, 2) the THD percent of the source current is within the standard limits, 3) the THD percent of the source voltage is within the standard limits, 4) the SEAPF mitigates all voltage problems, and 5) there is no need to use another filter (shunt or series and active or p)

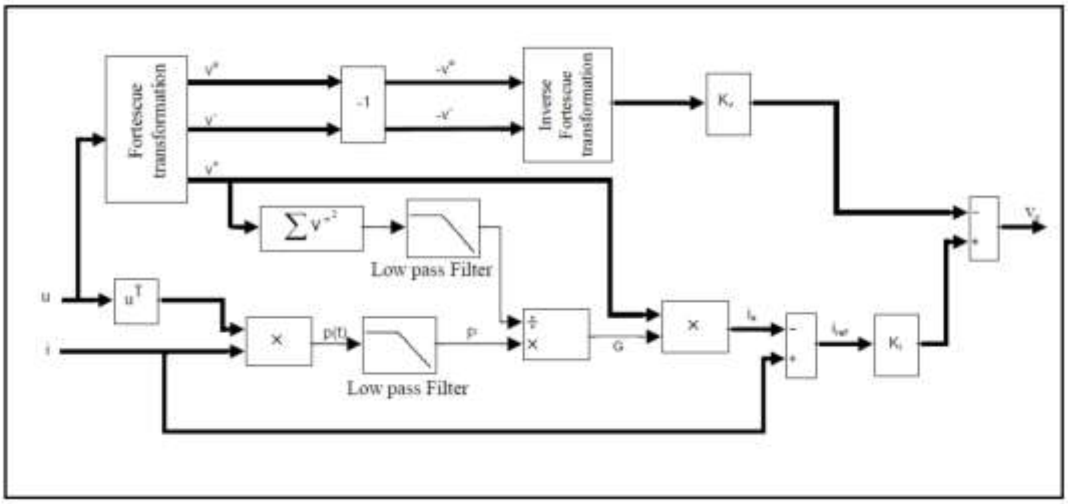

Fig.10. Blocks diagram of the control scheme

III. CONCLUSION

Harmonics, reactive power, and imbalanced load currents are all examples of power quality issues that may be mitigated by an Active Power Filter. These disturbances can cause highly automated systems to fail and sensitive loads linked to a point of common coupling (PCC) to malfunction, increasing the fault's economic impact. APF can be a highly successful option for high-tech industrial facilities or a group of clients in Custom Power Park or Power Quality Park that have sensitive loads. The converter topologies and control methods were the major focus of this research. APF topologies have been examined in detail. The findings of APF research in the literature and application notes of APF in service are provided in this study, allowing the trends of APF to be clearly recognised throughout time.

IV. CONCLUSION

This article provides an overview of PVS fault detection and diagnosis methods. PV's dependability, efficiency, and operating cost have all become critical elements in increasing its competitiveness in the energy market. Many approaches for problem identification and diagnosis have been studied in attempt to overcome this issue, as illustrated in this study.

Methods based on ANN and FL can differentiate between faults with similar signatures and categories potential problems. The primary disadvantages are that they need more sophisticated abilities in terms of real-time implementation (experimental realisation) and databases (of various defects), which are not always accessible.

This article provides an overview of APF technology development. There is a brief discussion of harmonic distortion issues and their effects on electric PQ. The traditional passive filter mitigation approaches are described first, followed by the enhanced APF mitigation methods. It also examines several forms of reference signal estimating algorithms, which is an important component of the APF. A summary of the APF control techniques is provided. Finally, recent efforts to combine a PV system with a shunt APF are briefly described.

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